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PRODUCTION SCHEDULING IN CUT&FILL UNDERGROUND MINES USING SIMULATION

A Master's Thesis that has been submitted as a study to be examined for a degree of Master of Science on February 7th 2001.

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PREFACE

This Master's Thesis study has been carried out at Boliden Mineral AB, in Boliden, Sweden, during the period of June 5th – December 6th 2000.

I would like to thank my supervisor, Professor Pekka Särkkä for the interest he has indicated to this study and all the guidance I have received from him during my studies and this thesis work.

I also would like to thank Boliden Mineral AB for giving me the opportunity to do my thesis in Boliden. I wish to express my gratitude to my instructor, Dr. Ing. Sunniva Haugen for her help, guidance and patience.

I want to thank my dear friends and Vuorimieskilta for the unforgettable and joyful years.

I would like to thank my parents for all the support they have given me during all these years.

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Helsinki, 7th February, 2001

Sari Koivisto

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HELSINKI UNIVERSITY OF TECHNOLOGY **ABSTRACT OF MASTER'S THESIS**

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Simulation is a powerful tool to model and animate in detail almost any operation or process. Several studies have shown that simulation can also be used in the mining industry with success.

This thesis work was done for Boliden Mineral AB in Sweden. The purpose of this thesis was to investigate if and how simulation can be used to evaluate long-term effects of different approaches to operations scheduling in Boliden's cut&fill operations and how these different scheduling strategies and rules affect long-term production capacity and utilisation of faces and machines.

First a mine model was built using Boliden Mineral AB's Garpenberg Norra mine as an example. Various data of Garpenberg Norra mine was collected from the database. Once all the input data required was collected programming the model was started. Five alternative scheduling strategies were simulated with various simulation times that range from 1 week to 12 weeks.

The conclusion of this thesis work is that it is possible to test alternative scheduling strategies by using simulation. No significant differences were found between tested rules. Different scheduling rules/strategies were found to optimise different goals. If the emphasis is on ore tonnages then the strategy to be used is different than if the emphasis is on the face utilisation, for example.

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Simulointi on oivallinen työväline miltei minkä tahansa toiminnon tai prosessin mallintamiseen ja animointiin. Useat tutkimukset ovat osoittaneet, että simulointia voidaan käyttää menestyksellisesti myös kaivosteollisuudessa.

Tämä Diplomityö tehtiin Boliden Mineral AB:lla Ruotsissa. Diplomityön tarkoituksena oli tutkia jos ja kuinka simulointia voidaan käyttää arvioimaan erilaisten aikatauluttamisstrategioiden vaikutuksia pitkällä aikavälillä maanalaisissa täyttölouhinta-menetelmää käyttävissä kaivosoperaatioissa sekä kuinka nämä erilaiset aikatauluttamisstrategiat vaikuttavat pitkän aikavälin tuotantokapasiteettiin sekä perien ja koneiden käyttöasteisiin.

Aluksi rakennettiin kaivosmalli, jonka perustana käytettiin Bolidenin Garpenberg Norra-kaivosta. Garpenbergin tietokannoista kerättiin kaikki tarvittava tieto, jota tarvittiin mallin rakentamiseen. Tämän jälkeen tehtiin kaivosmallin ohjelmoiminen. Kaikkiaan viisi erilaista aikatauluttamisstrategiaa mallinnettiin ja lopulta simuloitiin eri pituisin ajan jaksoin, jotka vaihtelivat yhdestä viikosta kahteentoista viikkoon.

Yhteenvetona voidaan sanoa, että erilaisten aikatauluttamisstrategioiden simuloiminen on mahdollista. Tässä työssä strategioiden välille ei löytynyt suuria eroja. Voidaankin sanoa, että oikean strategian valitseminen riippuu aivan siitä, minkälaiset tavoitteet on asetettu. Esimerkiksi, jos tavoitteet ovat korkeassa malmintuotannossa valittava strategia on aivan toinen kuin jos tavoitteena on korkea perien käyttöaste.

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1 INTRODUCTION

1.1 Background

In 1999 Boliden Mineral AB introduced simulation as a tool for evaluation of mine designs, optimisation of short-term production plans and training of operators and management. Two Boliden mines; one underground cut&fill operation and one open pit have been modelled. The simulation software used is AutoMod [1]. These models have been used to investigate the effects of equipment availability, workforce schedules, ramp designs, number of production units, etc.

A project called FlowProcessMine aims at improving the mines' ability to produce according to plan and reduce the production costs, by improving short-term operations management. Improving operations management includes improving the information systems, methods and tools for planning and scheduling as well as organisational issues. As a part of this project Boliden Mineral AB wishes to evaluate the appropriateness of their existing scheduling procedures, priority rules etc. Simulation is an alternative tool for production planning and scheduling that will be evaluated and possibly implemented in FlowProcessMine.

1.2 Goal of thesis work

The purpose of this thesis was to investigate if and how simulation can be used to evaluate the long-term effects of different approaches to operations scheduling in Boliden cut&fill operations.

Questions to be considered were:

- Can simulation be used to test the long-term effects of different schedules and scheduling strategies?

- Can a mine's results be improved by using appropriate manual decision rules and scheduling procedures?

- How do different strategies and rules affect long-term production capacity, utilisation of faces and machines, variations in production level, etc?

This thesis work should produce a "test-model" of a typical Boliden cut&fill mine that can simulate the effects of alternative production schedules.

2 BOLIDEN MINERAL AB

2.1 General

On December 10, 1924 the exploration drill holes hit the Boliden ore in the Fågelmyren swamp and that caused gold fever breaking out in Boliden. Since then, Boliden has opened and operated approximately 50 mines in Sweden and abroad. One of these is the Boliden mine, which was the largest and richest gold mine in Europe at the time [2]. Today Boliden's mining operations are located in Canada, Chile, Spain and Sweden.

Boliden mines and smelts copper, zinc, lead, gold and silver. Large integrated operations include exploration, technology sales, metal recycling and the manufacture of semi-finished copper products. Boliden was listed on the Toronto stock exchange in Canada in 1997 as an independent company, Boliden Limited.

2.2 Cut&Fill Mines of Boliden Mineral AB

Garpenberg, Kristineberg, Renström and Petiknäs mines in Sweden and Myra Falls mine in Canada are currently using cut&fill mining methods.

Cut&fill stoping is an underground mining method, in which an excavation cut is completed and backfilled before another cut is made. Cut&fill mining is primarily utilised for steeply dipping vein deposits and large, irregularly shaped deposits.

Garpenberg, which is located in the Swedish County of Dalarna, consists of two mines, Garpenberg and Garpenberg Norra, and one concentrator [3]. Garpenberg's mineral deposits were mined as early as the 13th century. Boliden purchased the Garpenberg mine from AB Zinkgruvor in 1957. Operations at the Garpenberg Norra mine started in 1972. The mines are located three kilometres apart and consist of a number of different sized, generally steeply dipping ore lenses.

Complex ore, containing copper, lead, zinc, silver and gold is mined at Garpenberg. The ore from the Norra mine contains zinc with some lead and silver. Ore is extracted by cut&fill

and undercut and fill methods. Both mines employ a combination of underground shafts and inclined ramps for transport of materials and personnel through the mine and the mined ore to underground crushers. Once crushed, ore is hoisted to surface through vertical shafts. Mining is carried on to depths of approximately 800 and 1000 metres at the Garpenberg and Garpenberg Norra mines, respectively. One million tonnes of ore are extracted from the two Garpenberg mines each year. Proven ore amounts to approximately six million tonnes. The number of employees is about 300. Garpenberg mill has the capacity to treat 1.0 million tonnes of polymetallic ore per year to produce zinc, copper/precious metals and lead concentrates.

Kristineberg, Petiknäs and Renström are part of Boliden Area Operations (BAO) [4]. Ore is extracted by cut&fill underground methods. From the BAO mines ore is transported by trucks to the BAO mill over distances, which vary from 25 to 90 kilometres.

Kristineberg is the deepest mine in Sweden, with mining carried out at depths below 1000 metres. It is also the oldest in the Boliden area, with operations started in 1940. Complex ore, which contains a number of metals, such as copper, lead, zinc, gold and silver, is mined in Kristineberg. The mine employs 170 people and has an annual production of approximately 560 000 tonnes.

Complex ore is also extracted at the Renström mine, which was opened in 1952. The mine employs 80 people and has an annual production of 115 000 tonnes.

The Petiknäs mine, located next to Renström, began operations in 1992. Here too, copper, lead, zinc, gold and silver are extracted. There is a 2.5 kilometre long tunnel between Petiknäs and Renström at a depth of 800 metres through which a train carries ore from Petiknäs to Renström where it is later hoisted to surface. About 560 000 tonnes of ore is extracted annually and the number of employees is about 85.

Myra Falls consists of two, H-W and Battle Gap, underground polymetallic mines [5]. The mines are located on Vancouver Island in Canada. Ore within the mines consists of a variety of generally shallow-dipping, zoned, polymetallic disseminated to massive sulphide bodies along a 6000 metre long and up to 460 metre thick stratigraphic sequence.

Until 1999, ore was being extracted using bulk underground mining methods. During 1999, Boliden introduced more controlled cut&fill mining methods to reduce dilution in certain areas of the mines. A 1.8 kilometre long underground rail line at the 24- metre level connects the Battle Gap mine to the H-W mine and the shaft. Crushed ore, personnel and materials are hoisted to surface through the vertical shaft. Mining is carried out to depths of approximately 700 metres. The mill at Myra Falls has the capacity to treat 1.1 million tonnes of ore to produce zinc and copper/precious metals concentrates. Crushed ore hoisted to surface is transported one kilometre by conveyor to the mill.

3 SIMULATION

3.1 Simulation as a tool

A simulation is an imitation of the operation of various kinds of real-world facilities and processes. Simulation is an indispensable problem-solving methodology for the solutions of many real-world problems. A simulation model can be developed to study, describe and analyse the behaviour of the system as it evolves over time, ask "what-if" questions about the real system and aid in the design of real system. This model usually takes the form of a set of assumptions concerning the operation of the system. These assumptions are expressed in mathematical, logical and symbolic relationships between the entities of the system. After the model has been developed and validated it can be used to investigate a wide variety of "what-if" questions about the real-life system. Simulation modelling can be used both as a design tool predicting the impact of changes on performance of existing systems, and as a tool to predict the performance of a new system under varying sets of circumstances.

Figure 1 shows a schematic of a simulation study. The iterative nature of a process is indicated by the system under study becoming altered system, which again becomes the system under study, and the cycle is repeated [6].

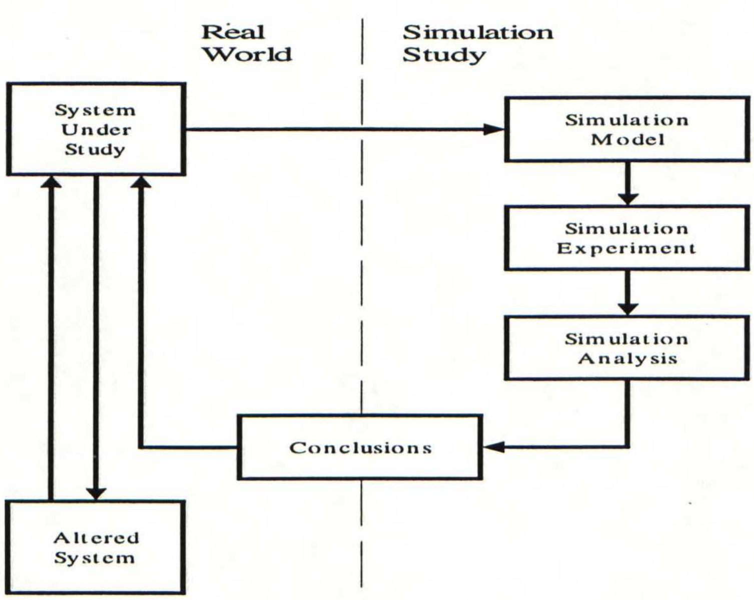


Figure 1. Schematic of Simulation Study [6].

In some cases it is possible to develop a model, which is simple enough to be solved by mathematical methods. These kind of simple models can be solved using differential calculus, probability theory, algebraic methods, or other mathematical techniques. However, most complex, real-world systems with stochastic elements cannot be accurately described by mathematical models that can be evaluated analytically. In these instances, numerical, computer-based simulations can be used to imitate the behaviour of the system over time.

Simulation is one of the most widely used and accepted tools in operations research and systems analysis due to the availability of special-purpose simulation languages, massive computing capabilities at decreasing cost per operation, and advances in simulation methodologies. Simulation is an appropriate tool for several occasions and can be used for e.g. following purposes [7]:

- Simulation enables the study of, and experiment with, the internal interactions of a complex system, or of a subsystem within a complex system.
- Informational, organisational and environmental changes can be simulated and the effect of these alterations on the model's behaviour can be observed.
- The knowledge gained in designing a simulation model may be of great value toward suggesting improvement in the system under investigation.
- By changing simulation inputs and observing the resulting outputs, valuable insight may be obtained into which variables are most important and how the variables interact.
- Simulation can be used as a pedagogical device to reinforce analytic solution methodologies.
- Simulation can be used to experiment with new designs or policies prior to implementation, so as to prepare for what may happen.
- Simulation can be used to verify analytic solutions.

Simulation is used in numerous applications in production and operations that range from assembly line scheduling to factory design. Examples include areas of manufacturing, material handling, transportation and construction systems, food processing, computer system performance and business process reengineering. Manufacturing and material handling systems provide one of the most important applications of simulation. Simulation has been used successfully as an aid in the design of new production facilities, warehouses and distribution centres. It has also been used to evaluate suggested improvements to existing systems. Engineers and analysts using simulation have found it valuable for evaluating the impact of capital investments in equipment and physical facility and proposed changes to material handling and layout. Managers have found simulation useful in providing a "test drive" before making capital investments and before disrupting the existing system with untried changes. Simulation can also be used as a tool for training users to perform their tasks effectively. Flight simulators for training pilots have been available for a long time.

3.1.1 Advantages and Disadvantages of Simulation

Simulation has many advantages as well as some disadvantages. Banks and al. [7] list these. The advantages are:

1. New policies, operating procedures, decision rules, information chains, organisational procedures and so on can be explored without disrupting ongoing operations of the real system.
2. New hardware designs, physical layouts, transportation systems and so on can be tested without committing resources for their acquisition.
3. Hypotheses about how or why certain phenomena occur can be tested for feasibility.
4. Time can be compressed or expanded allowing for a speed up or slow down of the phenomena under investigation.
5. Insight can be obtained about the interaction of variables.
6. Insight can be obtained about the importance of variables on the performance of the system.
7. Bottleneck analysis can be performed indicating where work in process, information, materials, and so on is being excessively delayed.
8. A simulation study can help in understanding how the system operates rather than how individuals think the system operates.
9. "What if" questions can be answered. This is particularly useful in the design of new systems.

The disadvantages are:

1. Model building requires special training. It is an art that is learned over time and through experience. Furthermore, if two models on the same subject are

constructed by two competent individuals, they may have similarities, but it is highly unlikely that they will be the same.

2. Simulation results may be difficult to interpret. Since most simulation outputs are essentially random variables (they are usually based on random inputs), it may be hard to determine whether an observation is a result of system interrelationships or randomness.
3. Simulation modelling and analysis can be time consuming and expensive. Skimping on resources for modelling and analysis may result in a simulation model or analysis that is not sufficient for the task.
4. Simulation is used in some cases when an analytical solution is possible, or even preferable. This is particularly true in the simulation of some waiting lines where closed-form queuing models are available.

3.1.2 Concepts of Modelling

In order to understand and analyse a system, a number of terms need to be defined.
The definitions in this work are mainly based on Banks and al., [7], Law and Kelton [8], Shannon [9], Bank [10] and Yingling [11].

A *system* is defined to be a collection of entities, e.g., people and machines that act and interact together toward the accomplishment of some logical study. An *entity* is an object of interest in the system. It is an item, which flows through the simulation. An entity can be a truck, a loader, maintenance personnel or any other item within the simulation. An entity can be any object that enters the system, moves through a series of processes and then leaves the system. An *attribute* is a property of an entity, and it is associated with the specific, individual entity. Attributes might be such things as name, priority, due date, required CPU time, ailment, account number etc. As entity flows through the system it will be processed by a series of *resources.* Resources are anything that the entity needs in order to be processed. Resources might for example be workers, material handling equipment, special tools etc. An *activity* represents a time period of specified length. It is a time-dependent action within the simulation such as the activity of loading a truck, driving the truck from the face to the ore-pass or loading the truck. A *process* is a time-ordered sequence of events that may involve several activities. The cycle of a truck being loaded, driving to the ore-pass, dumping its load and driving back to the loader could be defined as a process. An *event* can be considered as an occurrence that changes the state of the system. The *state* of a system is defined to be that collection of variables necessary to describe the system at any time, relative to the objects of the study. The term *endogenous* is used to describe activities and events occurring within a system, and the term *exogenous* is used to describe activities and events in the environment that affect the system.

Systems can be categorised as discrete or continuous. A *discrete system* is one for which the state variables change instantaneously at separated points in time. The bank is an example of a discrete system since the state variable, the number of customers in the bank, changes only when a customer arrives or when a customer finishes being served and departs. A *continuous system* is one in which the state variables change continuously over time. An aeroplane moving through the air is an example of a continuous system, since the state and variables such as position and velocity can change continuously with respect to time. Few systems in practice are wholly discrete or wholly continuous, but since one type of change predominates for most systems, it will usually be possible to classify a system as being either discrete or continuous. Mining is considered to be a discrete system.

Different ways in which a system might be studied is shown in *Figure 2* [8].

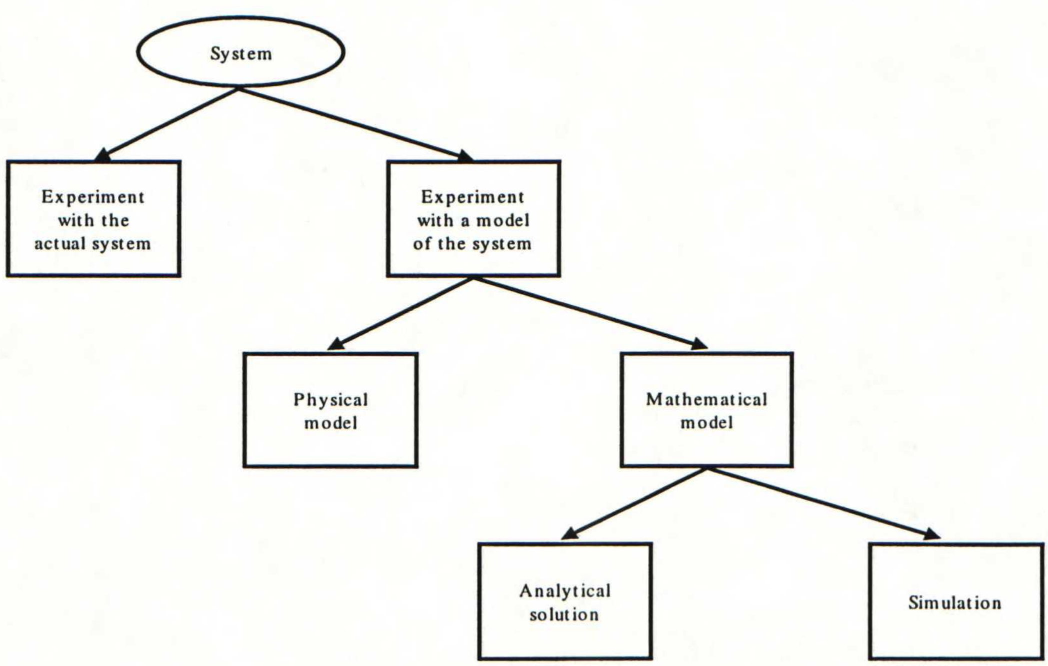


Figure 2. Ways to Study a System [8].

- *Experiment with the Actual System vs. Experiment with a Model of the System:* If it is possible to alter the system physically and then let it operate under new conditions it is probably desirable to do so. However, it is rarely feasible to do this because such an experiment would often be too expensive or disruptive to the system. It is usually necessary to build a model as a representation of the system and study it as a surrogate for the actual system.

- *Physical Model vs. Mathematical Model:* Physical models are not typical for models that are usually of interest in operations research and systems analysis. However, occasionally it has been found useful to build physical models to study engineering or management systems; for example a tabletop scale models of material-handling system. The vast majority of models built are mathematical, representing a system in terms of logical and quantitative relationships that are then manipulated and changed to see how the model reacts and how the system would react if the mathematical model were a valid one.

- *Analytical Solution vs. Simulation:* Once the mathematical model has been built, it must then be examined to see how it can be used to answer the questions of interest about the system it is supposed to represent. If the model is simple enough, it may be possible to work with its relationships and quantities to get an exact, analytical solution. However, many systems are highly complex, so that valid mathematical models of them are themselves complex. This precludes any possibility of an analytical solution, and in this case the only way to study the model is simulation. This means, that the model inputs have to be exercised numerically in order to see how they affect the output.

3.1.3 The Simulation Process

Figure 3 shows the steps in a simulation study. The number beside each step in *Figure 3* refers to the more detailed discussion in the text. The steps in a simulation study according to Banks and al. [7] are as follows:

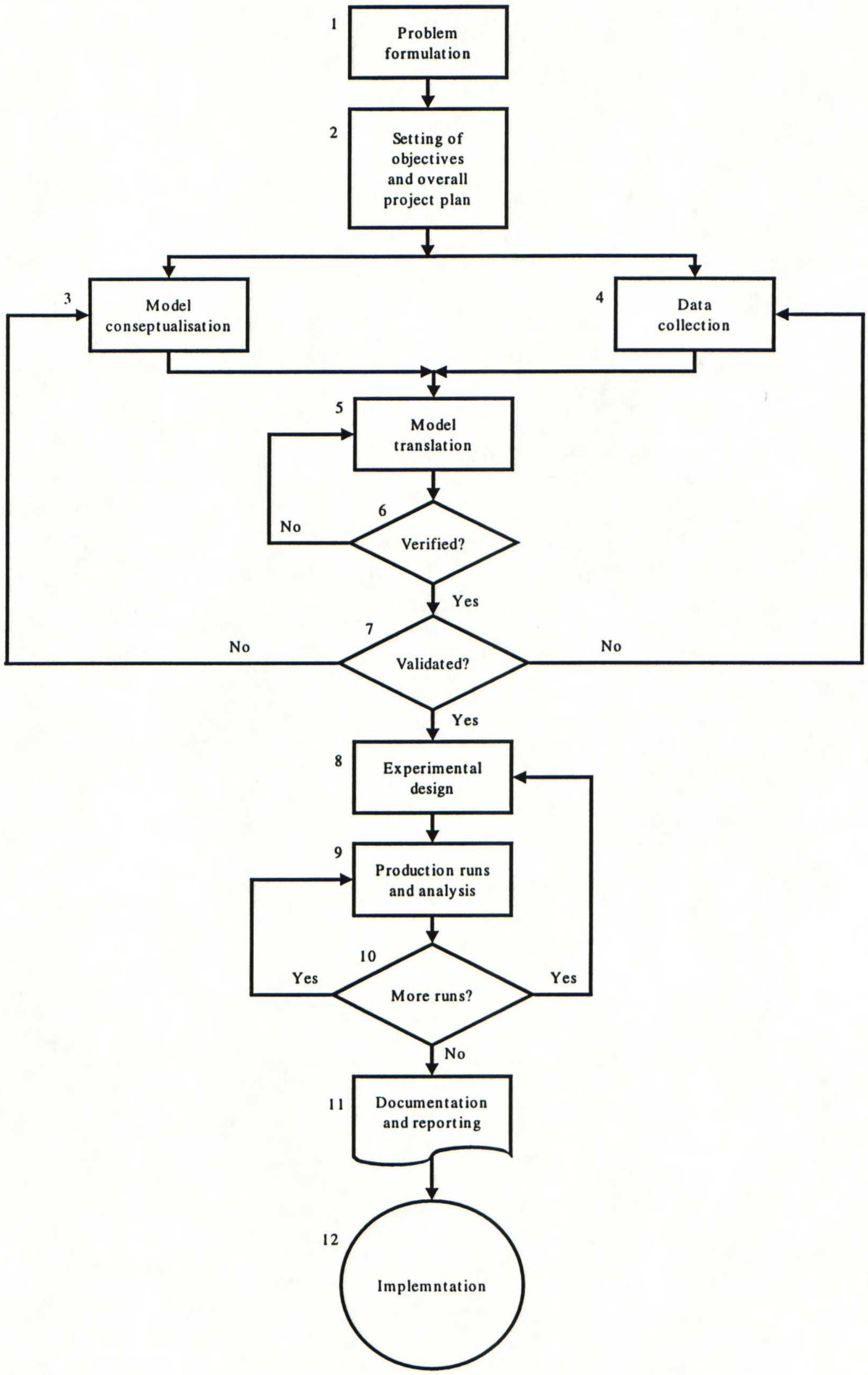


Figure 3. Steps in a Simulation Study [7].

1. **Problem formulation.** Every simulation study begins with a statement of the problem. If the statement is provided by those who have the problem (client), the simulation analyst must take extreme care to insure that the problem is clearly understood. If a problem statement is prepared by the simulation analyst, it is important that the client understands and agrees with the formulation. In some occasions the problem has to be reformulated as the simulation study progresses.

2. **Setting of objectives and overall project plan.** The objectives indicate the questions to be answered by simulation. The project plan should include a statement of the various scenarios that will be investigated, and a method for evaluating the effectiveness of these alternatives. The plans for the study should be indicated in terms at time that will be required; personnel that will be used, hardware and software requirements if the client wants to run the model and conduct the analysis, stages in the investigation, output of each stage and cost of the study.

3. **Model conceptualisation.** The real-world system under investigation is abstracted by a conceptual model, a series of mathematical and logical relationships concerning the components and the structure of the system. It is recommended that modelling begins simply and that the model grows until appropriate complexity has been developed. However, the model complexity does not need to exceed that required to accomplish the purposes for which the model is intended. Constructing an unduly complex model will add to the cost of the study and the time for its completion without increasing the quality of the output. Maintaining client involvement will enhance the quality of the resulting model and increase the confidence of the model user in the application of the model.

4. **Data collection.** There is a constant interplay between the construction of the model and the collection of the needed input data. As the complexity of the model changes, the required data elements may also change. Also, since data collection takes such a large portion of the total time required to perform a simulation, it is necessary to begin with it as early as possible, usually together with the early stages of model building. The objectives of the study dictate, in a large way, the kind of data to be collected. Model building and data collection are shown as

contemporaneous in Figure XX. This is to indicate that the simulation analyst can readily construct the model while data collection in progressing.

5. **Model translation.** Since most real-world systems result in models that require a great deal of information storage and computation, the model has to be entered in a computer in a recognisable format. The modeller must decide whether to program the model in a special simulation language or using special multi-purpose simulation software. Simulation languages are usually more powerful and more flexible than the special-purpose software. However, if the problem is amenable to solution with the special-purpose software, the model development time is greatly reduced. Furthermore, most of the special-purpose software packages have added features that enhance their flexibility, although the amount of flexibility varies greatly.

6. **Verification.** Verification pertains to the computer program prepared for the simulation. Is the computer program performing properly? With complex models it is difficult, if not impossible, to translate the model successfully in its entirety without a good deal of debugging. If the input parameters and logical structure of the model are correctly represented in the computer, verification has been completed. It is highly advisable that verification takes place as a continuing process. For the most part, common sense is used in completing this step

7. **Validation.** Validation is the determination that the conceptual model is an accurate representation of the real system. Validation is usually achieved through calibration of the model, an iterative process of comparing the model to actual system behaviour and using the discrepancies between the two, and the insights gained, to improve the model. This process is repeated until model accuracy is judged acceptable.

8. **Experimental design.** The alternatives that are to be simulated must be determined. Often, the decision concerning which alternatives to simulate may be a function of runs that have been completed and analysed. For each system design that is simulated, decisions need to be made concerning the length of the initialisation period, the length of simulation runs, and the number of replications to be made of each run.

9. **Production runs and analysis.** Production runs, and their subsequent analysis, are used to estimate measures of performance for the system designs that are being simulated.

10. **More runs?** Based on the analysis of the runs that have been completed, the simulation analyst determines if additional runs are needed and if any additional scenarios need to be simulated.

11. **Documentation and reporting.** There are two types of documentation: program and progress. Program documentation is necessary for numerous reasons. If the simulation model is going to be used again by the same or different analyst, it may be necessary to understand how the simulation model operates. This will enable confidence in the simulation model so that the model users can make decisions based on the analysis. Also, if the model is to be modified, this can be greatly facilitated by adequate documentation. One experience with inadequately documented program is usually enough to convince an analyst of the necessity of this important step. Another reason for documenting a model is to allow model users to change parameters of the model at will in an effort to determine the relationships between input parameters and output measures of performance, or to determine the input parameters that "optimise" some output measure of performance. Progress reports provide the important, written history of a simulation project.

Project reports give chronologies of work done and decisions made. This can prove to be of great value in keeping the project on course. Frequent reports (monthly, at least) are suggested so that even those not involved in the day-to-day operation can keep abreast. The awareness of these others can usually enhance the successful completion of the project by surfacing misunderstandings early, when the problem can be solved easily. Maintaining a project log is also suggested. It provides a comprehensive record of accomplishments, change requests, key decisions and other items of importance.

The results of all the analysis should be reported clearly and concisely in a final report. This will enable the model users (now, the decision makers) to review the final formulation, the alternative systems that were addressed, the criterion by which the alternatives were compared, the results of the experiments and the recommended solution to the problem. Furthermore, if decisions have to be justified at a higher level, the final report should provide a tool of certification for the model user/decision maker and add to the credibility of the model and the model building process.

12. **Implementation.** The success of the implementation phase depends on how well the previous 11 steps have been performed. It is also contingent upon how thoroughly the analyst has involved the ultimate model user during the entire simulation process. If the model user has been thoroughly involved during the model-building process and if the model user understands the nature of the model and its outputs, the likelihood of a vigorous implementation is enhanced. Conversely, if the model and its underlying assumptions have not been properly communicated, implementation will probably suffer, regardless of the simulation model's validity.

3.2 Verification and Validation of Simulation Models

3.2.1 Verification and Validation Processes

A significant element of any simulation study should be verification and validation (V&V) of the simulation model. Without thorough V&V there are no grounds on which to place confidence in a study's results. That said, V&V is far from straightforward and is often not performed as thoroughly as it might be.

Verification is the process of ensuring that the model design (conceptual model) has been transformed into a computer model with sufficient accuracy [12], in other words, building the model right. Validation, on the other hand, is the process of ensuring that the model is sufficiently accurate for the purpose at hand, in other words, building the right model. A key concept is the idea of sufficient accuracy; no model is 100% accurate. However, in V&V the aim is to ensure that the model is sufficiently accurate. The amount of accuracy required should be specified prior to starting the development of the model or very early in the model development process.

In the validation process three basic approaches are used in deciding whether a simulation model is valid or invalid [13]. Each of the approaches requires the model development team to conduct validation and verification as part of the model development process. The most common approach is for the development team to make the decision as to whether the model is valid. This is a subjective decision based on the results of the various tests and evaluations conducted as part of the model development process.

Another approach, often called " independent verification and validation" (IV&V), uses a third (independent) party to decide whether the model is valid. The third party is independent of both the model development team and the model sponsor/user(s). After the model is developed the third party conducts an evaluation to determine its validity. Based upon this validation, the third party makes a subjective decision on the validity of the model.

The advantages of an IV&V process are many [14]:

- Provides an objective assessment of the product during its creation.
- Adds a new analytical perspective not present in the development environment.
- Brings its own set of tools and techniques to bear on ensuring development accuracy and validity.
- Introduces "intermediate" users of the system who serve as "beta testers" before the product goes to market.
- Significantly enhances testing and the discovery of design flaws and coding errors.

Sargent's [13] view is that complete IV&V evaluation is extremely costly and time consuming for what is obtained, and that if a third party is used, it should be during the model development process. Sargent also suggests that if the model has already been developed, the third party usually should evaluate only the verification and validation that has already been performed.

The last approach for determining whether a model is valid is to use a scoring model [13]. Scores (or weights) are determined subjectively when conducting various aspects of the validation process and then combined to determine category scores and an overall score for the simulation model. A simulation model is considered valid if its overall and category scores are greater than some passing score(s). This approach is infrequently used in practice because (1) the subjectiveness of this approach tends to be hidden and thus appears to be objective, (2) the passing scores must be decided in some (usually subjective) way, (3) a model may receive a passing score and yet have a defect that needs correction and (4) the score(s) may cause over confidence in a model or be used to argue that one model is better than another.

There are two common ways how the model verification and validation relate to the model development process. One way uses some type of detailed model development process and the other uses some type of simple model development process. The simple way more clearly illuminates model verification and validation. *Figure 4* shows the simplified version of the modelling process.

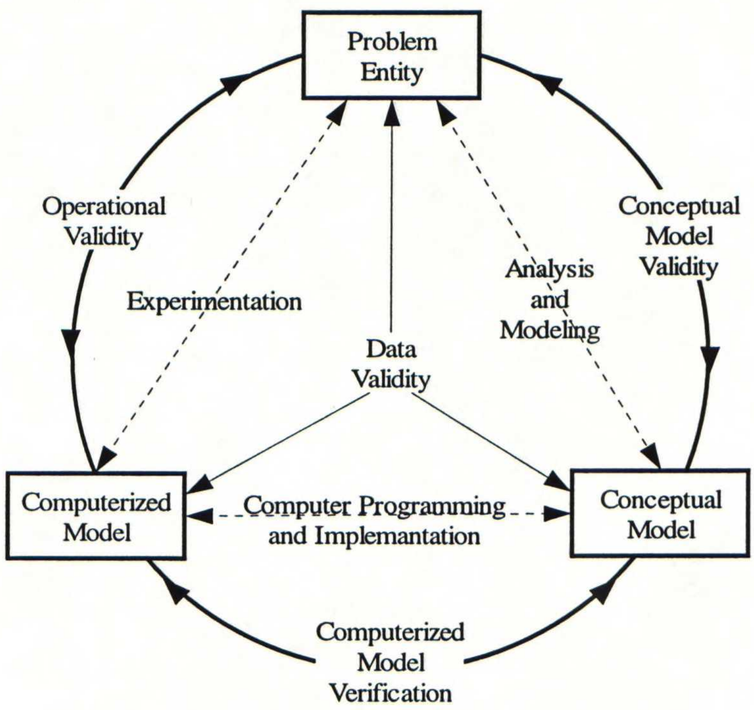


Figure 4. Modelling Process [13].

The *problem entity* is the system (real or proposed), idea, situation, policy or phenomena to be modelled; the *conceptual model* is the mathematical/logical/verbal representation (mimic) of the problem entity developed for a particular study and the *computerised model* is the conceptual model implemented on a computer. The conceptual model is developed through an *analysis and modelling phase*, the computerised model is developed through a *computer* *programming and implementation phase* and inferences about the problem entity are obtained by conducting computer experiments on the computerised model in the *experimentation phase*.

Conceptual model validity is defined as determining that the theories and assumptions underlying the conceptual model are correct and that the model representation of the problem entity is "reasonable" for the intended purpose of the model. *Computerised model verification* is defined as ensuring that the computer programming and implementation of the conceptual model is correct. *Operational validity* is defined as determining that the model's output behaviour has sufficient accuracy for the model's intended purpose over the domain of the model's intended applicability. *Data validity* is defined as ensuring that the data necessary for model building, model evaluation and testing and conducting the model experiments to solve the problem are adequate and correct.

Several versions of a model are usually developed in the modelling process prior to obtaining a satisfactory valid model. During each model iteration, model validation and verification are performed and a variety of validation techniques are used.

3.2.2 Validation Techniques

There are various validation techniques used in model validation and verification [13]. They can be used either subjectively or objectively. By "objectively" means using some types of statistical test or mathematical procedure, e.g. hypothesis tests and confidence intervals. A combination of techniques is generally used.

Animation: The model's operational behaviour is displayed graphically as the model moves through time. For example, the movements of parts through a factory during a simulation are shown graphically.

Comparison to Other Models: Various results (e.g. output) of the simulation model being validated are compared to results of other (valid) models. For example, the simple cases of a simulation model may be compared to known results of analytic models or the simulation model may be compared to other simulation models that have been validated.

Degenerate Tests: The degeneracy of the model's behaviour is tested by appropriate selection of values of the input and internal parameters. For example, does the average number in the queue of a single server continue to increase with respect to time when the arrival rate is larger than the service rate.

Event Validity: The "events" of occurrences of the simulation model are compared to those of the real system to determine if they are similar. An example of events is deaths in a fire department simulation.

Extreme Condition Tests: The model structure and output should be plausible for any extreme and unlikely combination of levels of factors in the system, e.g. if in-process inventories are zero, production output should be zero.

Face Validity: "Face validity" is asking people knowledgeable about the system whether the model and/or its behaviour are reasonable. This technique can be used in determining if the logic in the conceptual model is correct and if a model's input-output relationships are reasonable.

Fixed Values: Fixed values (e.g., constants) are used for various model input and internal variables and parameters. This should allow the checking of model results against easily calculated values.

Historical Data Validation: If historical data exist (or if data are collected on a system for building or testing the model), part of the data is used to build the model and remaining data are used to determine (test) whether the model behaves as the system does.

Historical Methods: The three historical methods of validation are *rationalism, empiricism* and *positive economics*. Rationalism assumes that everyone knows whether the underlying assumptions of a model are true. Logic deductions are used from these assumptions to develop the correct (valid) model. Empiricism requires every assumption and outcome to be empirically validated. Positive economics requires only that the model be able to predict the future and is not concerned with a model's assumptions or structure.

Internal Validity: Several replications (runs) of a stochastic model are made to determine the amount of (internal) stochastic variability in the model. A high amount of variability may cause the model's results to be questionable and, if typical of the problem entity, may question the appropriateness of the policy or system being investigated.

Multistage Validation: Sargent [13] writes about combining the three historical methods of rationalism, empiricism and positive economics into a multistage process of validation. This validation method consists of (1) developing the model's assumptions on theory, observations, general knowledge and functions, (2) validating the model's assumptions where possible by empirically testing them and (3) comparing the input-output relationship of the model to the real system.

Operational Graphics: Values of various performance measures, e.g. number in queue and percentage of servers busy, are shown graphically as the model moves through time; i.e., the dynamic behaviours of performance indicators are visually displayed as the simulation model moves trough time.

Parameter Variability-Sensitivity Analysis: This technique consists of changing the values of the input and internal parameters of a model to determine the effect upon the model's behaviour and its output. The same relationships should occur in the model as in the real system. Those parameters that are sensitive, i.e., cause significant changes in the model's behaviour or output, should be made sufficiently accurate prior to using the model. Model development consists of several logical steps and one of them should be the determination of parameters, which are most influential on model output [15].

Predictive Validation: The model is used to predict the system's behaviour and then comparisons are made between the system's behaviour and the model's forecast to determine if they are the same.

Traces: The behaviour of different types of specific entities in the model is traced through the model to determine if the model's logic is correct and if the necessary accuracy is obtained.

Turing Tests: People who are knowledgeable about the operations of a system are asked if they can discriminate between the system and model outputs.

3.2.3 Model Verification

Model verification deals with building the model right. The accuracy of transforming a problem formulation into a model specification is evaluated in model verification [16]. Computerised model verification ensures that the programming and implementation of the conceptual model are correct. The programming language used is the major factor affecting verification [13].

When a simulation language is used, verification is primarily done to ensure that an error free simulation language has been used, the simulation language has been properly implemented on the computer and that a model has been programmed correctly in the simulation language. The primary techniques used to determine that the model has been programmed correctly are *structured walk-throughs* and *traces* [12].

If a higher-level language has been used, then the computer program should have been designed, developed and implemented using techniques found in software engineering. In this case verification is primarily done to determine that the simulation functions and the computer model have been programmed and implemented correctly.

It is necessary to be aware while checking the correctness of the computer program and its implementation that errors may be caused by the data, the conceptual model, the computer program or the computer implementation.

3.3 Simulation in mining

After a 40-year history, several things have changed and several have remained rather static in mining simulation. Most surveys of operations research procedures in mining operations have shown that statistics and simulation are the most common procedures used to help in optimising the mining process. These two methods constitute more than half of all operations research applications and this ratio has not changed significantly. The area of application of simulation within mining has also been rather constant with materials handling application being predominant. Another similarity over the years is that simulation is applied primarily to cyclic materials handling processes. This includes trucks, LHDs, and various types of loaders. [17]

Today typical mining models involve the estimation of the production capability of a system or conversely, determining the system required to achieve production targets. The modelling process takes account of large number of parameters and evaluates the impact of changing either a single parameter or several combined. Mining simulation models could evaluate the impact of such things as [18]:

- Numbers of various categories of workers and their work rosters.
- Number of various types of equipment in use.
- Equipment operating characteristics, such as loading and dumping times, travelling speeds, capacities, treatment rates etc and variations for different types of materials handled.
- Equipment maintenance parameters, including both planned and random breakdowns.

- Capacity and spacing of passing areas for trucks or trains etc.
- Existence and capacity of surge bins and stockpiles.
- Characteristics of rock to be handled, such as patterns of availability of different rock types, digability, drawpoint hangup characteristics etc.
- Blending, product quality and delivery schedule constraints.

Recent projects around the world in the area of mine simulation include, for example, a model of a surface iron ore mine in the USA that is using a dispatcher [19], a model of a new mining sequence in a South-African diamond mine [20] and a model to aid in the production scheduling of an underground copper mining operation in Brazil [21].

In the minerals industry simulation modelling started to grow during the early 1960s when digital computers became commonplace. Today computer simulation is one of the most successful analytical applications of computers in mining through the world. Through simulation, managers and engineers can explore the impact of new technologies, equipment designs, plans and operating strategies to improve their operations. For example, using a simulation model before any new piece of equipment is introduced into the mine, it can be "tested" in the computer model to see what the effect on the production will be. The animation model then shows the results of the proposed changes. A lot of money can be saved by simulating an operation before making substantial investments in changes or initial design of a system.

Mining engineers have long been interested in using computers to construct simulation models of their mining operations. Most of the early applications of simulation in the mining industry were performed with user-written codes programmed in Fortran for use in mainframe computers. The early applications were predominantly simulations of haulage systems, and haulage problems associated with tracks, belts and trucks were analysed. As the usefulness of simulation in engineering and business became evident, computer software specialists began to program simulation elements into software packages that allowed more expedient building of simulation models. The software package elements were assembled into conceptual models and utilised by means of simulation languages [17].

As computers developed over the time so did simulation languages. "Traditional" engineering computer languages such as Fortran, Pascal, and Basic etc. have been mostly replaced by special languages, designed specially for discrete system simulation. A typical mining system might take many employee-months to model using a language such as Fortran. The system can be modelled in a matter of few minutes using a special language. Each of these special languages has evolved over the years and different forms of each exist [22]. These special languages greatly reduced the user time spent on designing and running the models. The development of computer hardware and software technology during the 1990s has made the development of more demanding simulation programs possible. Large mine-wide simulation programmes concentrate on describing the system and giving information on the operations through the mine lifetime. The latest development focuses on applications that can be used during mining for operational and process guiding purposes.

The *GPSS* (General-Purpose Simulation System) language was the first general-purpose simulation language to gain widespread favour. It dates from the early 1960s when it was developed by IBM. It was once made an "open file" so a great many variations have evolved. A few of these are: GPSS/II, GPSS 360, GPSS/R, GPSS/PC, GPSS V, GPSS V/S and GPSS/H. GPSS is a process-oriented simulation language that is well suited for queuing systems. GPSS has been used, for example, in a large coal mine in the Western Unites States, where the company using the program wanted to study the changes that needed to be made to the mining system when production increased by a factor of around 40% [22].

Arena is an extendible simulation and animation package. Arena is popular in many applications, from traditional manufacturing to forestry to mining. Arena is fairly new and is designed to allow the user to rapidly construct simulation and animation models using icon templates. Arena has been used, for example, to study the operation of the ore trucks and the loaders in a congested area [22].

ModSim III, SimFactory and *SimProcess* softwares were developed by CACI. ModSim III is an object-oriented, general-purpose programming and simulation language. SimFactory is a flexible factory planning tool and with it the user can out the flow of resources, documents, people etc. easily. SimProcess is a business re-engineering and process tool. SimProcess has been used, for example, to study the material flow for a gold mine [22]. This software is easy to use and the models are developed quickly.

SLAM is one of the more popular simulation languages for modelling discrete systems and there have been a few references in the literature to mining systems modelled using this language [22]. The language is Fortran-based and it appears to be one of the easier packages to use for generating simulation and animation models.

Witness is visually interactive, user-friendly simulation system, but it has not found widespread use for mining applications. In 1995 Laurentian University Mining Automation Laboratory carried out a work in close collaboration with the Mines Research Department at Inco Ltd., in Sudbury, Canada [22].

AutoMod is an interactive industrial simulation modelling environment that has been adapted to model mining systems as well. AutoMod was used, for example, to evaluate the future evolution and automation of an underground mine using Vertical Retreat Mining method at Inco mine in Canada [23]. AutoMod is the software used in this thesis work and therefore it will be handled in more detail in Chapter 3.4.

Sandvik Tamrock Corp has developed an underground rock flow simulation tool called *OPTIMINE*, which is a direct simulation tool for matching suitable technology in rock material flow for underground mine layouts and production requirements [24]. The tool gives the possibility of determining intersections, limitations and critical points in the layout and working procedures at an early stage of a new mine/mining area planning process.

3.4 AutoMod

AutoMod is simulation software developed by AutoSimulations Inc [1]. It combines the features of a general-purpose simulation language and a special purpose material-handling simulator. The AutoMod simulation system differs from other systems because of its ability to deal with the physical elements of a system in physical (graphical) terms and the logical elements of a system in logical terms. AutoMod offers advanced features to allow users to simulate complex movements (kinematics and velocity) of equipment such as robots, machine tools transfer lines and special machinery [25].

AutoMod's movement systems aid users in defining the movement of material either manually or by automated equipment. Material movement systems include:

- Path Mover (path/vehicle systems such as lift, trucks, AGVS and human movers)

- Conveyors (including belt and roller types)
- Automated Storage and Retrieval Systems (ASRS)
- Robots
- Bridge Cranes
- Power and Free Chain Conveyors

To define material movement systems, the user simply creates geometric entities, such as paths and stations, and then inputs the operating parameters, such as velocity and acceleration. AutoMod automatically creates the corresponding logic for the movement system. 3-D animation is created automatically as well, providing a realistic picture of how a facility will operate. Model animation can be viewed from any angle or perspective, providing visualisation capabilities unmatched in other simulation systems.

AutoMod software fits well for simulation of mining systems. It has several advantages [25]:

- The ease of use even in very large, complex systems,
- Provision of adequate debugging and error diagnostics,
- Capability to import from other software, such as spreadsheets and CAD (Computer-Aided-Design) packages and
- Ability to be combined without programming with animation/graphics environments for visualisation of the operations.

4 SCHEDULING

4.1 Production Scheduling in Underground Mines

Production scheduling is an integral part of the mine planning process. Mine designs are prepared iteratively, with constant reassessment of the mining schedule. The process is necessarily laborious and only a minor part of it can be computerised.

Scheduling is required for the development and production activities in underground and open pit mines. Types of schedules include [27]:

- Life of mine plan
- 5 year plan
- Annual plan
- Monthly plan
- Weekly plan
- Shift plan

The objectives of underground scheduling include:

- Providing a steady and balanced ore feed to the mill or a steady blended product for direct shipping.
- Maximising the NPV of the project by accessing higher grades early and always filling the mill with the best available feed.
- Providing a steady, balanced workload for the development and production equipment fleets.
- Deferring development as long as possible consistent with access for exploration, infill drilling and stope development.
- Setting development rates which are unit multiples of the capacity of a standard development crew or fleet.
- Minimising the numbers of active working areas to reduce the cost of supervision and services.

- Minimising the time development has to be kept open in recognition that there is a maintenance cost for development.
- Maximising the size of stopes or stoping blocks while keeping a minimum number of active stopes to protect against stope outages.
- Providing time in the development and stoping cycle for surveying, infill drilling, planning, ground support, and production drilling.
- Sequencing the stopes from bottom up or from top down according to the mining method and filling requirements.
- Minimising the requirement for pillars.
- Minimising stocks of broken ore, which tie up working capital and ore at risk of re-cementing.
- Stope sequencing according to geotechnical requirements to control mining-induced stresses.
- Maintaining ventilation and services as required.
- Provide a steady usage of backfill and maximise the utilisation of backfill material.
- Minimise the need to remove development waste from the mine.

It is usual to have rules of thumbs about maintaining development ahead of production. As an example here is a long hole stoping operation, and rules in such an operation might be:

- Primary access development two years ahead of production.
- Stope development one year ahead of production.
- Production drilling six months ahead of production.
- Stocks of broken ore for three months.

In some another operation these times might be halved depending on the size of stopes and past experience of possible production disturbances.

Each longhole stope will have a production profile, which includes a build-up, a period of steady production, then a tailing off and final cleanup. This can be modelled as three equal time intervals:

- 25% of tonnes, rate starts at zero and rises to full rate
- 50% of tonnes at full rate

- 25% of tonnes, starting at full rate and falling to zero.

This production profile must be recognised when scheduling. The production profile is shown in *Figure 5*.

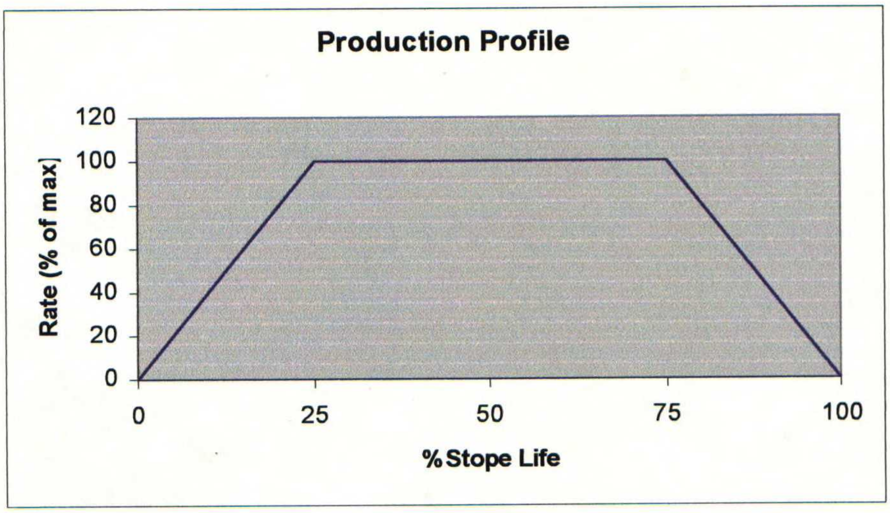


Figure 5. Production Profile [27].

The full rate will be determined not by absolute size of the stope but by the number of draw points and the production mucking capability, including orepass and haulage capacities.

The steps in underground production scheduling are as follows:

1. Define stope and stoping method.
2. Calculate diluted tonnes and grades for each stope.
3. Select the mining sequence, defining primary and secondary stopes and permanent pillars, with the aim of satisfying the objectives of previously listed.
4. Re-define stopes if necessary to suit the schedule. Repeat the above steps if required.
5. Estimate the production profile for each stope and prepare a time line showing how consistent production is maintained.
6. Check the filling schedule and match the stoping schedule if required.
7. Schedule the necessary development with key points being the provision of ventilation and services.
8. Check the required development rates and modify the stoping schedule if they are excessive.

Underground mine scheduling requires a much greater geological knowledge than open pit scheduling. In an open pit, a statistical approach to ore occurrences may be taken provided the expected tonnage and grade are found "somewhere on the bench". An underground mine requires detailed geological interpretation and "hard" boundaries to the orebody model.

Development rates should be set at some multiple of the capacity of a jumbo or development crew working efficiently with good utilisation. The degree of flexibility will depend on the industrial relations environment and whether multi-skilling exists. There is a modern trend not to distinguish between development and production operators.

The achievable development rate will depend on the number of personnel and equipment, the number of available faces, travelling distance between faces and the ground support requirement. If the raise boring is contracted out, schedules should be based on campaigns, which minimise mobilisation costs.

The importance of the filling schedule should not be underestimated. A useful measure is the cumulative void, which is the difference between the mining and filling schedules. If this continues to grow the instability or loss of access are likely.

Short-term scheduling covers the time period from 1 shift to one week. Short-term scheduling is basically operations control. The main target is to keep up the production by keeping all the operations in schedule. If the work stays in schedule the production targets are also achieved.

In short-term scheduling decisions are made regarding [28]:

- Work face selection
- Activity
- Equipment
- Workers

Equipment and operators are assigned to activities and work faces. There are several criteria how to choose a working face. The simplest methods are just to follow the plan or continue on a previous face. A work face can also be chosen depending on grades and volumes, sometimes is favourable to try to mine high-grade ore or "fast" tonnes in order to keep up the production target. The difficultness of the face might also affect on a work face selection, an "easy" face might be preferred to a difficult one as the work proceeds faster on the easy face and higher production rate is achieved in a shorter period of time. Probably the most used strategy when selecting a work face is to choose the one that is most behind the schedule. Travelling time to the face might also affect when selecting a work face. A face that is close to the current location of equipment is preferred to the face that is located further away as time that is not spent for travelling can be used for working.

Activities and different mining cycles have to be taken into consideration when doing short-term planning. Mining cycle can be fixed for every blast, meaning that activities are following each other in the same order every time. Sometimes only certain activities are performed on each round and other activities at fixed interval. For example, all the other activities are performed on each round but bolting and shotcreting are done only on every fifth round. Rock support, surveying etc can also be done only when needed without including them to the mining cycle and fixing a specific schedule for them.

Assigning equipment to the activities depends on few things. Naturally, it is based on the required activity that a piece of equipment has to perform and conditions of the workplace. Travelling distance may also affect on the decision how to appoint equipment to the activities. Availability of equipment plays of course an important role. Preventive maintenance may take out the machine that is still working perfectly well, and this may cause some conflicts between a production foreman and maintenance personnel. One should not despise the importance of the preventive maintenance.

Workers can be divided to two groups: multiskilled workforce and specialists. Multiskilled workers can perform variety of activities and they are more flexible when it comes to scheduling. A specialist performs only a specific activity he has skills for, for example, drilling or loading. Having specialists as workforce has many advantages: they take better care of equipment, they gain better results in their work and in the beginning of shift there is no need to sign in machines for workers, which can be time consuming.

4.1.1 Software for Planning and Scheduling

Some geological modelling and mine planning software (e.g. Datamine, Surpac, Medsystem) includes a scheduling function. This may be based on linear programming or other optimisation techniques.

Generic scheduling packages such as Timeline, Harvard Total Project Manager and Microsoft Project can be all used for mine scheduling at the cost of substantially simplifying the considerations involved. These are really PERT/Critical Path Method programs and do not deal successfully with incremental tonnages and weighted average grades, or the interaction between development, stoping and filling schedules.

More complex project management tools such as Prima Vera can be adapted to mining. They are most successful if used for an annual budget where the possible variations are not great. Prima Vera (which is also ported to Windows) and similar packages are really designed for the construction of high-rise buildings or bridges and tracking components down to the "last nut and bolt". The form of output is not suited to mining so it is best downloaded into a spreadsheet for final analysis and presentation. It is a trap to develop a very complex multi-year model using the above systems, because changes, which inevitably occur in mining practice, render the subsequent schedule meaningless.

Any system more complex than the generic ones like MS Project will require a dedicated operator. As with geological modelling system, constant involvement is required to maintain skill levels after an initial learning period. Care must be taken to ensure that the scheduling function is well documented and sufficiently simple that staff transfers can be accommodated regularly without total disruption of the planning function.

Most mine scheduling can be done using ordinary spreadsheets. These are very flexible and easily understood by others. Presentation using graphs, bar charts and time bars is excellent. Spreadsheets handle the grade and tonnage computations while leaving the engineer free to consider the problem "holistic".

Most of these softwares described above are used for long-term scheduling. There are hardly any softwares designed solely for short-term scheduling. Usually short-term scheduling is done using software packages meant for long-term scheduling or manually.

4.2 Scheduling in Boliden cut&fill mines

The planning and scheduling process in the underground mines of Boliden is shown schematically in *Figure 6.*

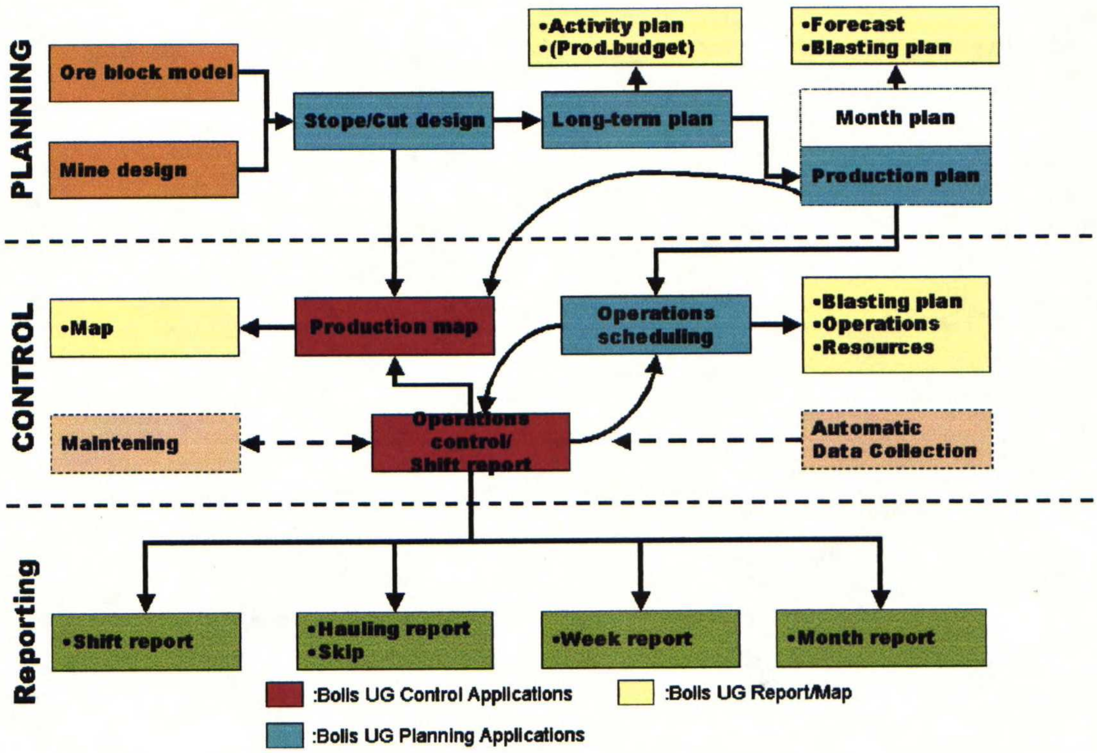


Figure 6. *Boliden Underground Mine Planning and Scheduling Process [29].*

Planning and scheduling has a basis in a proper design of a mine. The mine planner receives a 3D-block model of ore body from the geologist. The ore model includes e.g. locations of ore, ore boundaries and grades. Using this geological data the *mine design* is created. Mine design shows dimensions of rooms and pillars, position of pillars and stopes, main access ramps, shafts, ventilation, crusher, etc. Mine design is divided into smaller units, *stope designs*. Stope design comprises a detailed design for 2-3 cuts ahead and a rough design for other cuts. In stope design cut height, positions of access drifts, possible local ramp systems and infrastructure, number of cuts from each access and extraction method are determined. Production profile for the stope is created, cost-revenue calculations are made on alternative designs and the best one is chosen. Average tons and grades are determined as well as required meters of development per cut. Stope design is created from the ore block model and mine design using MicroStation, which is a CAD-software. Calculations of grades and tonnages for the stope as whole and for every cut are made.

Cut design is developed from the stope design and it is for cuts to be mined next 18 months. By sectioning 3D-stope at selected heights stope boundaries for each cut are got. Boundaries are adjusted based on latest geological information and design criteria. In the cut-design phase attributes are added to the mining segments. In this phase the design covers only "outlines", no details are included with exception to the first 1-3 cuts to be mined. Accesses and alternative cut designs are adjusted and then new economical calculations are made. These calculations are the basis for the budget. Production profile is created for 3 cuts on basis of this information.

MicroStation add-ons are also used when doing cut design. When the cut design has been drawn, named, it has been given the attributes and the mining sequence has been decided the information is exported to the *production map*.

Production map is a graphical presentation of the area where mining is planned to take place together with the information about current location from the shift report and surveying. Production map is created from cut design and it is used in monthly and weekly production planning and operations control.

Drift design is the next step in designing. Width of drifts and sequence for drifts on each cut are determined. Stope boundaries are updated on basis of new geological information and because of this also information on tons and grades per drift are updated. Cost-revenue calculations are made for each lens and drift.

Blast design is created from the cut design. In blast design each drift is divided into blasts with given length and tons and grades for each blast are determined.

Different stages of design are the basis for long and short term scheduling in mines. Mine design gives the ground for *strategic planning*, cut design is the basis for *tactical planning*, and drift and blast designs are basis for *production planning*.

Strategic planning covers the time range from 1 year to life of mine. It determines the capacities, infrastructure, mining methods, cut-off grade, mining sequence and equipment selection and investment.

Tactical planning covers the time range from 1 to 18 months. Tactical planning is also called long-term planning. It is rolling scheduling of all stopes that are mined during the planning period and the plan is usually updated every 3 months. Stopes in production and the development rate for each stope are determined. This includes average cycle times for designed mining method and ground support requirements. Long- and short-term development is scheduled and using the resulting tons and grades the concentrator calculates a 3-month forecast to smelter. For cuts that will be mined during the first three months each blast is scheduled. Characteristics for short-term planning are that ore tonnage is based on actual blasts, not template tonnages and balancing critical operations (for example, cut-change, cable bolting, shotcreting). An important goal of the long-term planning is to balance production in a way that optimal utilisation of production systems and ore resources are achieved. Long-term planning is a basis for the production budget. In the beginning of each year the production budget is made. It is a special case of long-term plan and it is the forecast of ore production for the forthcoming year. In order to create and maintain a long-term plan BUMS (BolidenUndergroundMineScheduler) is used to combine data from design and production models.

Production plan covers 1-3 months and it is updated every month at monthly planning meeting. It is rolling scheduling of all cuts that are to be mined during the period. In production plan the blasts/positions to be mined each week and mining rate are determined. Target of the production planning is to adjust production to meet the long-term plan. Optimal utilisation of production resources (equipment and personnel) and ore flow (transport, tons, grades) are the most important success criteria in mine planning. Production plan provides input to blasting plan and production forecast.

A tool called *Month plan* is used to produce and maintain the rolling 3-month production plan. From the planned blast tempo the program calculates the production forecast (number of blasts, tonnage, waste rock dilution and grades) for each drift and total per planning period.

Operations scheduling covers the time period from 1 shift to 2 weeks and it is rolling planning of all blasts on all drifts that are blasted during the period. Operations schedule is updated once a week in the weekly planning meeting. In the operations scheduling the target is to optimise production when it is a question of utilisation of critical resources and drift-utilisation. Operation scheduling differs from production plan following ways: production plans treat all the blasts (blasting cycles) similar assuming that they are all equal in duration whereas the operation scheduling comprises unique blasts and different blasts can have different blasting cycles with different amount of operations, sequences and schedules.

All the operations that are included in a blasting cycle and are "reserving" drifts are scheduled in the operation planning. Characteristics for the operation scheduling are that each blasting cycle is unique (duration of operations, sequence and amount) and optimising operations sequence for each drift and blast in a way that amount of simultaneous operations of certain type (e.g. drilling) does not exceed the maximum amount of actual resources.

A tool called *Week plan* is used for operations scheduling, for example, scheduling all operations that are going to complete the blast cycle. Operation scheduling is a basis for the *operations control.*

Operations control consists of controlling all assignments that are performed during the shift. Shift foreman of the finishing shift plans the operations for the next shift; this is prioritising operations according to the operations schedule and deciding which persons/machines are going to be used. The target of the operations control is to keep all the operations on schedule. If the work is on schedule then the work is just going to follow operations schedule, but if the work is lagging behind the schedule then the "critical drifts" will be prioritised and drifts lagging less behind the schedule will follow. If operations control is successful the work will stay on schedule and the production targets are met, if it is not successful there is no chance to achieve the goals of the production budget. Data from production (operations, sequence, starting and finishing times) is collected to shift report and it is used to control production against current production plan.

5 SIMULATION OF OPERATIONS SCHEDULING IN CUT&FILL MINING

5.1 Development of Model

5.1.1 Alternative Scheduling Strategies

The purpose of this thesis work was to investigate what kind of long-term effects different scheduling strategies have on production capacity, utilisation of faces and machines, etc. 14 alternative scheduling procedures and decision rules were determined but after all only 5 of them were selected and simulated. Those five were thought to be the most interesting ones. Some of them are regularly used in the mines, some are considered to be quite extreme and used rarely. All the strategies that were considered in the beginning are described in the list below. The ones that were simulated are numbers 1-5; 'Most behind the schedule', 'First blast', 'Max volumes, max grades', 'Balancing grades' and 'Priority to difficult faces'.

1. Most behind the schedule

   In this strategy the face that is lagging most behind the schedule will be mined first. In order to simulate this kind of a strategy we have to know operation times for each activity in the cycle and when the next blast is scheduled. How much a face is lagging behind the schedule can then be found out by comparing the stages of current activities to the operation schedule. In ideal conditions there should not be any face that is lagging behind the schedule or any face that is ahead of the schedule.

2. First blast

   Work starts on a face that will be ready to be blasted first. This requires that the operation times for each activity on each face be known. By counting forward how many hours it will take until each face is finished and ready to be blasted we can find out which face will be ready to be blasted first. For example, there are two faces, Face A and Face B, which are under operations. It will take 6 hours until Face A will be ready for the blast and 8 hours until Face B will be ready for the blast. According to this strategy Face A will be prioritised.

3. Max volumes, max grades

   This requires that volumes and grades are included in the model, and that those faces with maximum volumes and highest grades are prioritised by always sending the equipment there when needed. The purpose of this strategy is to get maximum tonnage of high-grade ore. Only one metal can be prioritised at the time.

4. Balancing grades

   Target of using this strategy is achieving production with stable, balanced ore grade to allow the concentrator optimum working conditions. When tonnage and grades of each blast are known the simulation program can be told to mine faces, which will give the production with balanced ore grade. Only one metal can be balanced at the time.

5. Priority to difficult faces

   Faces have been categorised to three different categories 1, 2 and 3 according to their difficulty as indicated the tonnages of the faces. The more difficult the face is the more time it takes to finish the whole cycle. Number 1 represents easy face, number 2 medium and number 3 difficult face. This information is included in the Excel input sheet. The face to be prioritised is the face that is categorised as number 3.

6. Shortest time to finish operation

   Prioritising a working face where the current operation will be finished soonest. This requires that operation times for each activity are known in order to see how long it takes to finish a certain operation on a face and therefore choose the face, which will be finished with that operation after shortest period of time. For example, a loader is needed at two faces; on Face A the loader will be needed for loading, which would take 4 hours and on Face B it will be needed for cleaning, which would take half an hour. Face B will be prioritised as the activity takes shorter time to be finished on Face B.

7. Shortest time to start operation

   Prioritising a face that will be ready for activity with the shortest waiting time. Here we have to take into account both the waiting time until the face is ready for operation and the travelling time to the face. Travelling time is calculated from the travelling distance and the speed of a machine. For example, Face A will be ready for an operation in half an hour and travelling time to the face is 15 minutes, this adds up to the total waiting time of 45 minutes. Face B will be ready in one hour and travelling time to the face is 10 minutes, this adds up to the total waiting time of 70 minutes. In this case Face A will be prioritised, as its total waiting time is shorter than Face B's.

8. Shortest travelling time

   A face where to the travelling time is shortest will be prioritised. Basically, this means that the factors to be taken into account are the travelling distance and the speed of a machine. From that data the travelling times can be calculated and the most preferable face can be chosen. For example, it takes 25 minutes from the drillrig to travel to Face A from its current location and 15 minutes to Face B, thus Face B will be prioritised.

9. Delay as long as possible without changing blast time

   This strategy means that starting the work on a face is delayed to the latest point possible without changing the planned blast time. Here the blast plan is required and by calculating backward from the scheduled blast the latest starting time to an operation can be found out. For example, according to the blast plan Face X is scheduled to be blasted in the end of morning shift day after tomorrow. Face X is already ready for drilling but because drilling and charging will take only 4 hours these operations will be delayed to start morning shift day after tomorrow.

10. Balancing level in bins

    By looking at the production of previous week and the level in the ore bins the target production rate can be established. Knowing volumes of each blast the production can be controlled and the ore level in the bins can be balanced.

11. Utilisation of machines

    Once identified the bottleneck machines they have to be kept working. This is done by minimising the waiting time and the distance a piece of equipment has to travel to a workplace.

12. Assign machines to men and randomly assign available faces

    This is how the model is working at the moment. Basically first in-first out.

13. Prioritised blasts

    Forcing simulator to prioritise a certain drift before any other drifts. Other drifts where there is work to be done are selected randomly and they are using only the work force and/or equipment that is not needed on a prioritised drift.

14. Forced schedule each shift

    After a shift is finished and before next one starts simulation is stopped. Simulation is then forced to follow a manual schedule, which has been done for the next shift. This procedure follows each shift.

5.1.2 Mine Model

Constructing the mine model started from the scratch. Instead of using the already existing model of Petiknäs mine, totally new mine model was built. The existing Petiknäs model was found to be too complicated for the purpose of this thesis work and a simpler model was desired. This new model is based on the Garpenberg Norra mine. The mine model layout is shown in the *Figure 7.*

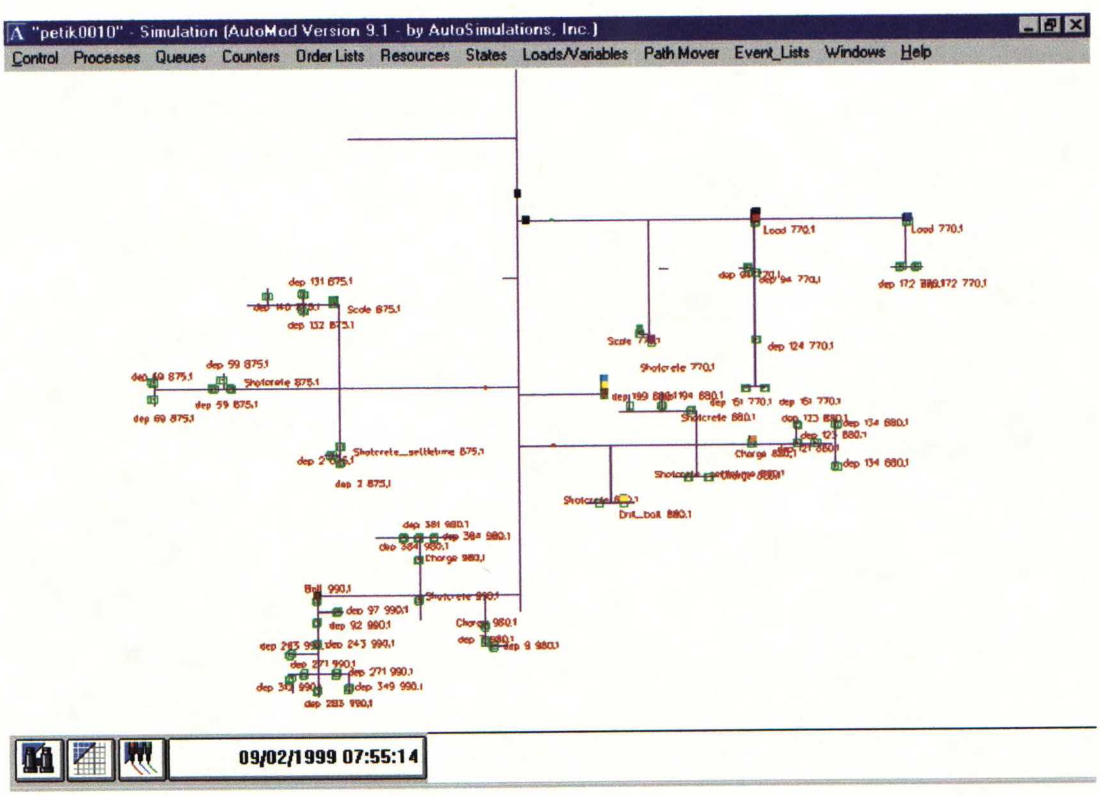


Figure 7. Mine model layout as seen in AutoMod.

The mine model is a highly simplified 2D-model with 4 working levels, 765, 865, 900 and 990. Each level has several drifts. Parking place/work shop is located in level 870, the rock that is classified to be ore is hauled to the level 800 where the crusher is located and the rock that is classified to be waste is hauled to the level 715. In a real mine waste rock is hauled to several locations depending on where it is needed, for example for backfilling purposes. In this model the waste rock is hauled only to one destination to make the model simpler because it cannot be predicted where the waste rock is needed as the model does not include further waste rock handling, for example for backfilling purposes. Ramp is connecting all the levels. All the working faces are marked with green squares and colourful blocks represent different mining machines, drillrigs, loaders, trucks, etc.

The model was built to imitate the real mine. The mine layout was made to look similar, although it is simplified, to the real mine, all the equipment used in the real Garpenberg Norra mine are also included into the model, shift times are the same as in Garpenberg etc.

There are 3 drillrigs in Garpenberg Norra as well as in the model. Two of them are primarily doing blasthole drilling and one of them is used for drilling boltholes. In a case when there are no blasthole drillrigs available for drilling blastholes also drillrig used primarily for bolthole drilling can be used to drill blastholes and visa versa. One charger is taking care of charging blastholes. There are two loaders in the mine, one loader is primarily doing all the loading after blasts and the other one is primarily used for cleaning the faces. Also the loaders do each other's tasks if required. Three trucks are used for hauling the rock either to the crusher if the rock quality is ore or to the level 715 if the rock quality is waste. There are also 2 scaling jumbos, 2 bolting rigs and a shotcrete jumbo in the mine.

The model can handle all these machines and, if required, the number of equipment can be easily increased. This is done in the Excel-interface where the required equipment is chosen. Specific data on the equipment is also included in the Excel-interface. This data includes capacity, speed (empty and loaded), Mean-Time Between-Failure (MTBF) and Mean-Time-To-Repair (MTTR) for each piece of equipment.

All the machines are assumed to be perfect in this simulation study; they do not break down, have down time or scheduled maintenance. It is possible to include Mean-Time Between-

Failure (MTBF) and Mean-Time-To-Repair (MTTR) to simulation but it can be quite difficult to simulate them accurately, especially in a short-term basis.

5.1.3 Excel Interface

The input related to the simulation is represented in the Excel interface. The interface includes several sheets where the input data are described. The data from Excel workbook is written to the data files, which are then read by the simulation model. Results of the simulation are written into this same Excel workbook. *Table 1* lists and describes the interface input data sheets and *Table 2* lists and describes the simulation output sheets.

Table 1. Input data sheets.

L765, L865, L900 and L990	Level information; cut, drift ID, blast #, blast dependency, cycle ID, scheduled blasting date&time, rock quality, advance, width& height of the face, tonnes, grades (Cu, Zn, Pb, Au and Ag)
Cycles	3 different mining cycles, operation times and frequencies, equipment required
Machines	Machine name, capacity, speed (loaded&empty), average MTBF & MTTR
Distances	Distances between levels, distances from the ramp to the crusher, waste storage, service/parking lot and working faces, backfilling data
Shift forms	Shift starting and finishing times, breaks and blasting times
Strategies	Strategy to be used, selection of target grade, different strategies
Other input	Warm-up and simulation times

There is a level information sheet for each working level. Each level has several drifts, some of the drifts have more than one cut, although, most of them are mined only in one cut. Each blast that takes place on the different levels is individual. Blasts are numbered, dependencies between the blasts are determined and each blast has scheduled blasting date and time. Depending on its size each blast has a cycle ID telling which mining cycle to follow. There are 3 different cycles, which are categorised according to their size; small blasts have shorter operation times than larger blasts. Operation frequency determines if the operation is performed on every cycle or if it is performed, for example, only on every second cycle. For example, it is a quite common practise that rock bolting is not done after every blast but first maybe 5 rounds are blasted and then the whole advance is bolted at once.

Distances-sheet includes several tables. Distances from the surface to all levels are given as well as the number of meeting points there are between the levels. At the meeting points machines can pass each other by when they are travelling on the ramp. Distances from the ramp to the crusher, waste storage and service/parking lot are also given here. Drift information table gives the distances from the ramp to the working faces as well as backfilling data for each drift. The backfilling data includes the time required for the backfill preparation work and the dependencies between the drifts when backfilling.

At the moment there is only one shift form available for the simulation model. It is possible easily to add more different shift forms to the model if needed. Shift form table describes the starting and finishing times of the shifts, starting and finishing times of the breaks and blasting times.

Strategies-sheet describes all the strategies, including the ones that were not simulated in this thesis work. In this sheet the user also selects the strategy he/she wants to simulate and depending on the strategy used, the metal that is prioritised. Only one metal can be prioritised at the time in the strategies number 3 and 4. Strategy number 3 is ' Max volumes, max grades' and number 4 is 'Balancing grades'.

The last input data sheet is used for selecting the warm-up period and simulation time.

Table 2. Output sheets.

Output	Tons of ore and waste total and per shift from each drift
MedProd	Average grades, amount of metals produced
Equipment	Equipment utilisation (off, idle, working, transport)
Drifts	Face utilisation (working, waiting, other)
Blasts	Actual blasting dates&times

Output generated by the simulation is written, as already mentioned earlier, to the Excel workbook. The simulation model does not collect data from the warm-up time, data collection starts as the actual simulation time begins. Data collected from the simulation is really basic numerical data, which can be used for evaluating the performance of the mine;

tons of ore and waste mined, amount of metals produced, average grades of metals, equipment and face utilisation and actual blasting times.

5.1.4 Logics of the model

In the beginning of the simulation the equipment is created on the parking place in level 870. Once all the equipment is on the parking place and the shift starts assigning work faces for the equipment begins. Simulation starts always from the beginning of the mining cycle, meaning that the drillrigs are the only machines, which can work first as they have to start the mining cycle by drilling blastholes. After a drillrig has finished drilling on a face a charger gets in and the cycle continues as described in the Excel-interface. Because mining in this simulation model always starts in a way from the scratch the beginning of the simulation does not correspond to the reality and this is the reason why the warm-up period has to be included. This makes it sure that the production is "normalised" by the time the actual simulation with data collection starts.

Assigning a piece of equipment to a specific face depends on the strategy used. If the strategy used is number 1, 'Most behind the schedule' priority is give to the face, which is lagging most behind the schedule and the piece of equipment is sent to that specific face, and so on. Different strategies were described in the chapter 5.1.1.

Work always follows the mining cycle described in the Excel workbook and the operations follow each other the same way every time. When a face is available for work it calls for a piece of equipment that can perform an operation needed. A piece of equipment travels from the parking place to the face, stays there the time required to finish the operation and then leaves back for the parking place. Machine frees the face and the face can call for the next piece of equipment needed. When the equipment is idle it is all the time checking for the work available until it finds something and can travel to a working face.

When a piece of equipment is travelling to a face it travels normally on a ramp, but once it enters a level it is "translated" to a face. "Translating" means that a piece of equipment is moved to the face without travelling in a level. It still spends the same time, as it would travel normally. Translating is just used to keep the model simple.

Working starts once the shifts begins, when it is time for a break machines just stop where they are and once the break is over they continue where they were left before the break. As mentioned earlier machines do not have MTBF, MTTR or any kind of down time, they do not have to be fuelled either so this means that the efficient working time is high compared to reality.

5.2 Simulation runs

Four different combinations of the warm-up periods and the simulation times were simulated for each of the five strategies. As described earlier the simulation model runs first the warm-up period without collecting data and after that it runs the actual simulation time when the desired data is collected into the output tables. Different combinations of the warm-up periods and the simulation times are shown in the *Table 3.*

Table 3. Warm-up periods and simulation times

Warm-up period	Simulation time
5	1
8	4
5	8
5	12

Simulation runs were made for every scheduling strategy and the results from the runs were combined and analysed. The output to be analysed were: tonnes of ore and waste mined, amount of metals produced, average grades of metals, equipment utilisation and face utilisation.

5.2.1 Tonnes of Ore and Waste Mined and Amount of Metal Produced

As an output this simulation study produced following measures:

- Tonnes of ore and waste mined
- Amount of metals produced
- Average grades of metals in the ore

Table 4 and *Figures 8-11* shows the tonnes of ore and waste mined with all the different combinations of simulation times and warm-up periods studied in this thesis work. In the following tables and figures names of the strategies are shortened by following ways:

- Behind the schedule = Beh.sched.
- First blast = 1. blast
- Max volumes, max grades = Max V&%
- Balancing grades = Bal. %
- Priority to difficult faces = Diff.face

Table 4. Ore and waste mined

Warm-up_Sim.time	Strategy	Beh.sched.	1. blast	Max V&%	Bal. %	Diff. face
5_1	Ore	25158	25326	19211	23981	24244
	Waste	276	276	2988	276	276
8_4	Ore	95190	94412	98770	78991	89865
	Waste	1569	1868	1601	11798	5214
5_8	Ore	191013	190144	187802	173127	184790
	Waste	2492	3073	7256	13903	6755
5_12	Ore	252506	251298	253116	241001	243346
	Waste	6624	5993	15916	20372	11420

When looking at the *Table 4, Ore and waste mined*, it seems, as there is some difference between alternative strategies, although it is not significant. It is easier to see the difference when the tonnages are presented percentage-wise. *Table 5* shows the ore tonnages percentage-wise; other tonnages are compared to the smallest one. Table shows how much more other strategies produce ore in comparison to the strategy that gives the smallest production.

Table 5. Ore tonnages percentage-wise

Sim.time_warm up	Beh.sched.	1. blast	Max V&%	Bal. %	Diff. face
1_5	31%	32%	0%	25%	26%
4_8	21%	20%	25%	0%	14%
8_5	10%	10%	8%	0%	7%
12_5	5%	4%	5%	0%	1%

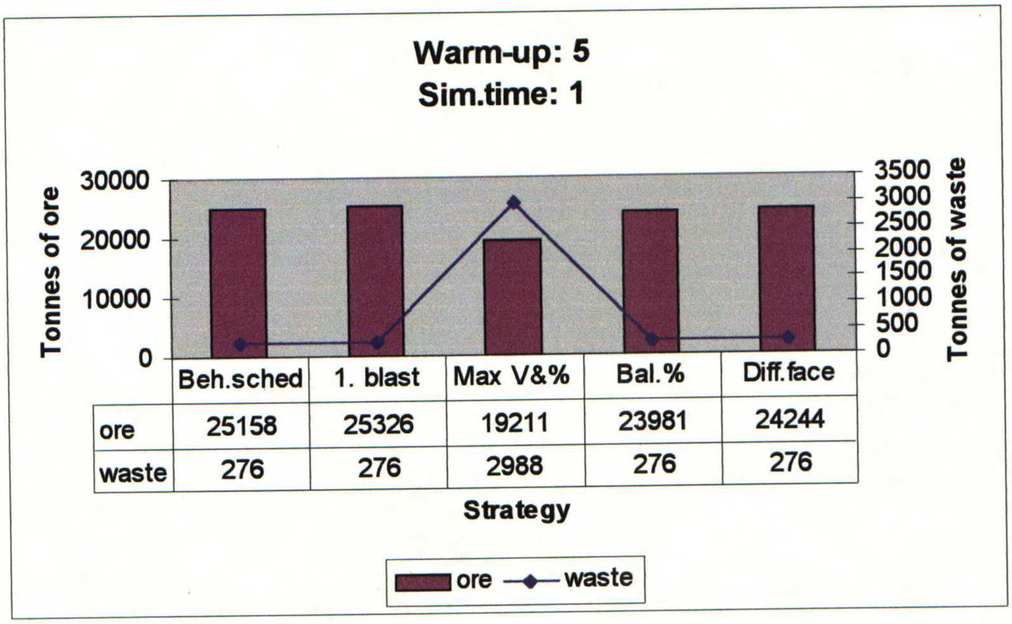
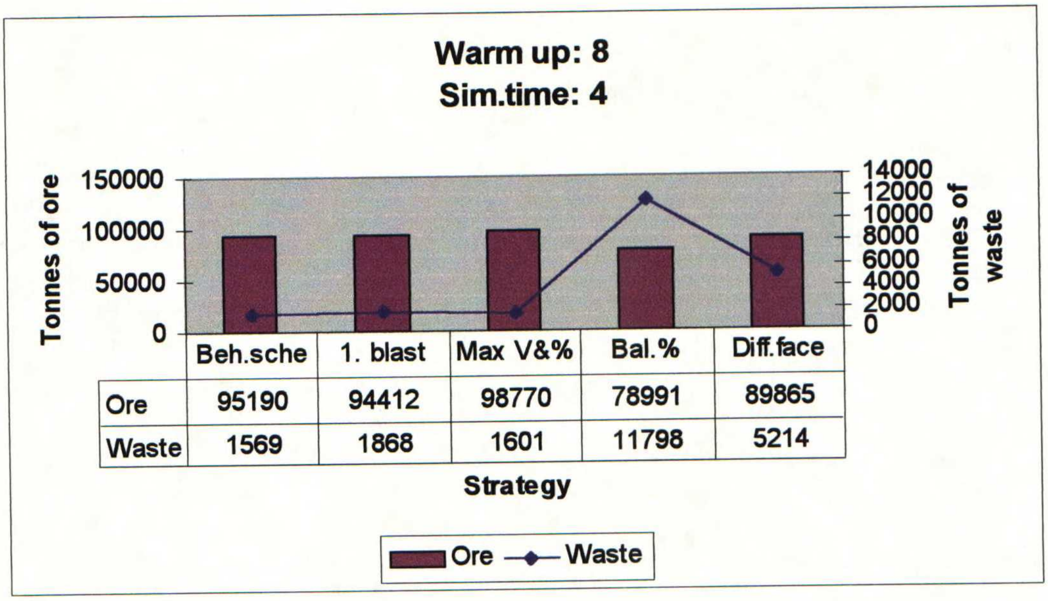


Figure 8. *Tonnes of ore and waste mined: Warm-up 5 weeks, simulation time 1 week.*

Figure 8 shows the tonnes of ore and waste mined when the warm-up period is 5 weeks and simulation time is 1 week. When looking at the *Figure*, it shows that tonnages are really similar with all the other strategies except the strategy number 3, which is 'Max volumes, max grades'. With this strategy ore tonnes are smaller than with other strategies and waste tonnes are much higher. This might seem a bit strange as the idea behind this strategy is to mine faces with great volumes and high grades. Explanation for this is a simple programming "error"; instead of only mining the blasts with great volumes of ore with high grades also the blasts with great volumes of waste are mined. This should not be the case, only rock quality "ore" should be accepted and ore with high grades and great volumes mined.

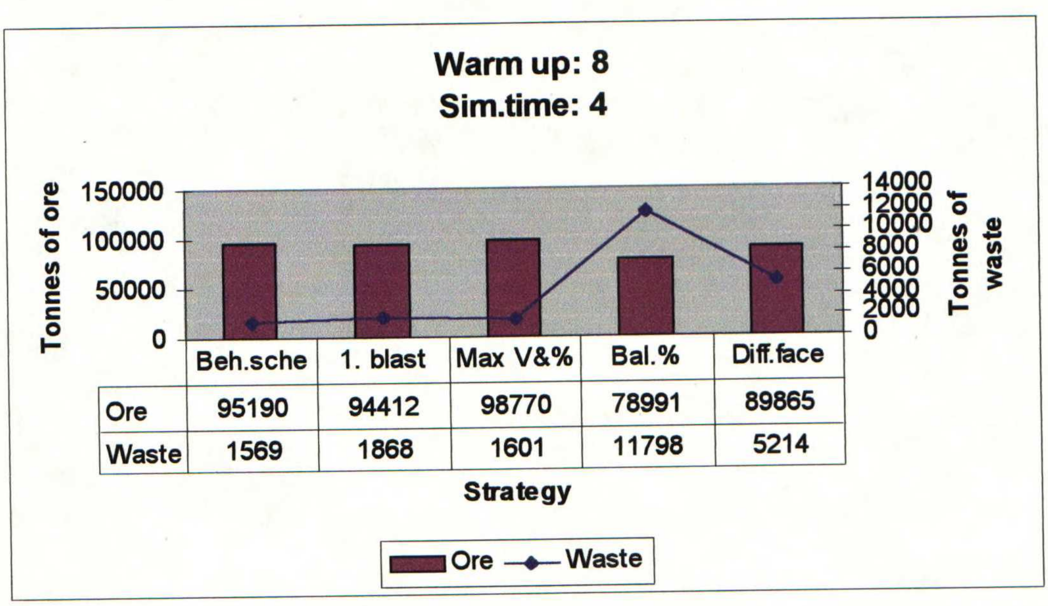
When looking at the *Table 5, Ore tonnages percentage-wise,* on the previous page it is easier to see that percentage-wise there is difference in production rates. Other strategies are compared to the strategy number 3 (Max volumes, max grades) as it gives the lowest production. Strategies 1 (Most behind the schedule) and 2 (First blast) give 32% and 31%, respectively, higher production than 'Max volumes, max grades', and strategies 'Balancing grades' and 'Priority to difficult faces' give 25% and 26%, respectively, higher production. If the strategy 'Max volumes, max grades' is not taken into account the differences in production rates between other strategies are really small and it is difficult to make any kind of conclusions out of that.



	Beh.sche	1. blast	Max V&%	Bal.%	Diff.face
Ore	95190	94412	98770	78991	89865
Waste	1569	1868	1601	11798	5214

Figure 9. *Tonnes of ore and waste mined: Warm-up 8 weeks, simulation time 4 weeks.*

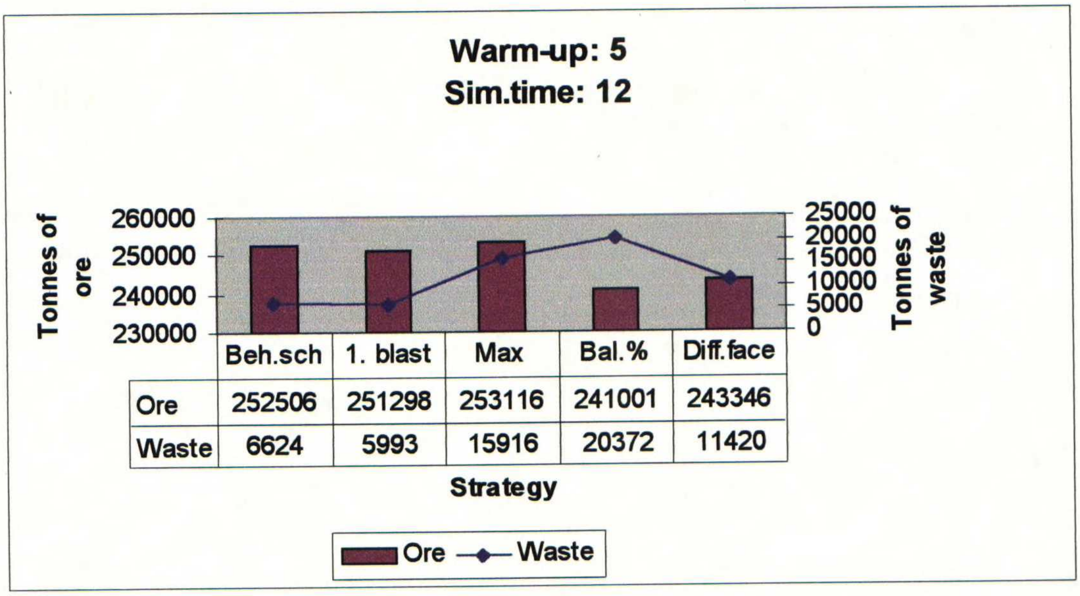
Figure 9 shows the tonnages of ore and waste mined when the warm-up period is 8 weeks and the simulation time is 4 weeks. Now the lowest ore production and the highest waste extraction come with the strategy number 4, (Balancing grades). Percentage-wise the difference in production between the strategy with the lowest production and other strategies is smaller than in previous case. Now the differences range between 14% and 25%. Strategy 'Max volumes, max grades' gives this time the highest tonnages contrary to the previous case when it gave the lowest production.



	Beh.sche	1. blast	Max V&%	Bal.%	Diff.face
Ore	95190	94412	98770	78991	89865
Waste	1569	1868	1601	11798	5214

Figure 10. *Tonnes of ore and waste mined: Warm-up 5 weeks, simulation time 8 weeks.*

Figure 10 shows the ore and waste extraction rates when the warm-up period is 5 weeks and simulation time is 8 weeks. Here again the strategy number 4, 'Balancing grades' gives the lowest tonnages of ore and the highest tonnages of waste. When comparing the production rates percentage-wise it can be seen that the trend is the same as it is with previous cases; ore production rates are similar with all the other strategies expect with the one that has the lowest ore production. Ore production rates of other strategies are 7% - 10% higher than production of 'Balancing grades'. This time the highest production rates are achieved with strategies 'Most behind the schedule' and 'First blast', both have 10% higher production than the strategy with the lowest production, 'Balancing grades'. Strategies 'Max volumes, max grades' and 'Priority to difficult faces' have ore production of 8% and 7% higher than 'Balancing grades'.



	Beh.sch	1. blast	Max	Bal.%	Diff.face
Ore	252506	251298	253116	241001	243346
Waste	6624	5993	15916	20372	11420

Figure 11. Tonnes of ore and waste mined: Warm-up 5 weeks, simulation time 12 weeks

The last set of simulation runs is a combination of warm-up period of 5 weeks and simulation time of 12 weeks. *Figure 11* shows the ore and waste extraction rates. Once again the strategy 'Balancing grades' gives the lowest ore production and the highest waste tonnage. From the *Table 5* it can be seen that the strategies 'Most behind the schedule', 'Max volumes, max grades' and 'First blast' give the highest production rates, 4% - 5% higher than 'Balancing grades' while the strategy 'Priority to difficult faces' only gives 1% higher production.

Average grades for each of the 5 metals were calculated from the ore tonnages and metals produced. *Table 7* shows the calculated average grades.

Table 7. Average grades

Sim.time_warm-up	Strategy	Units	Cu	Zn	Pb	Au	Ag
1_5	Beh. sched.	% or g/t	0.047	3.053	2.070	0.202	116.061
	1. blast	% or g/t	0.045	3.002	2.061	0.208	121.995
	Max V&%	% or g/t	0.044	3.034	2.162	0.217	144.805
	Bal. %	% or g/t	0.051	3.071	2.256	0.269	134.027
	Diff. face	% or g/t	0.057	2.857	2.226	0.238	133.294
4_8	Beh. sched.	% or g/t	0.055	3.242	2.194	0.258	147.660
	1. blast	% or g/t	0.060	3.226	2.197	0.250	145.731
	Max V&%	% or g/t	0.065	3.594	2.077	0.246	130.270
	Bal. %	% or g/t	0.060	3.396	1.894	0.220	131.664
	Diff. face	% or g/t	0.059	3.264	2.121	0.235	126.793
8_5	Beh. sched.	% or g/t	0.061	3.436	2.153	0.243	145.248
	1. blast	% or g/t	0.061	3.414	2.163	0.239	143.857
	Max V&%	% or g/t	0.057	3.370	1.866	0.214	129.199
	Bal. %	% or g/t	0.058	3.356	1.900	0.216	130.585
	Diff. face	% or g/t	0.064	3.440	2.073	0.234	133.352
12_5	Beh. sched.	% or g/t	0.058	3.312	2.075	0.227	135.868
	1. blast	% or g/t	0.058	3.312	2.086	0.228	135.780
	Max V&%	% or g/t	0.056	3.326	1.978	0.228	138.363
	Bal. %	% or g/t	0.058	3.330	2.031	0.224	133.073
	Diff. face	% or g/t	0.060	3.302	2.082	0.228	135.537

It can be seen from the *Table 7* that there is not significant difference in grades between different strategies and simulation times. Copper and gold grades stay quite stable through the simulation runs, there is a bit more variation in zinc and lead grades, but still the variation is not significant. Silver grades fluctuate the most. With the shortest simulation time the variation is the largest and when the simulation time is the longest, 12 weeks, the average grades for different strategies are closest to each other.

It seems that if the goal is to get highest tonnages of ore mined then the strategies 'Most behind the schedule' or 'Max volumes, max grades' should be chosen as they give the best ore production. If the high metal production is the goal then either 'Most behind the schedule' or 'Max volumes, max grades' should be chosen once again. 'Most behind the schedule' gives the highest silver production and 'Max volumes, max grades' gives the highest zinc production.

5.2.2 Equipment Utilisation

All the equipment has four states of status; a piece of equipment can be *idle, off, transport* or *working*. A piece of equipment is idle when it is available for work but there is no work it can do. Machine's status is off when it is not working during the shift change or break. The status of a machine is "transport" when the piece of equipment is travelling underground from one place to another and "working" when it is on a face and working. Trucks are in "transport" state when they are hauling rock and in "working" state when they are being loaded on faces.

Table 8 and *Table 9* show examples of equipment utilisation.

Table 8. Equipment utilisation: Strategy 4 (Balancing grades), simulation time 4 weeks, warm-up period 8 weeks

Resource	Sum	Off	Idle	Transport	Working
Drillrig_1	100%	25%	26%	5%	44%
Drillrig_2	100%	25%	25%	6%	44%
Drillrig_3	100%	25%	25%	6%	44%
Charger_1	100%	25%	16%	8%	51%
Loader_1	100%	23%	28%	3%	45%
Loader_2	100%	23%	28%	3%	46%
Truck_1	100%	21%	29%	31%	19%
Truck_2	100%	21%	29%	31%	19%
Truck_3	100%	20%	29%	32%	19%
Scaler_1	100%	25%	55%	2%	17%
Scaler_2	100%	25%	54%	3%	18%
Boltingrig_1	100%	25%	37%	2%	36%
Boltingrig_2	100%	25%	38%	2%	35%
Shotcretejumbo_1	100%	25%	1%	3%	71%

When comparing the equipment utilisation of different simulation run sets there are not really significant differences between alternative strategies. Of course off-time and time used for travelling stays pretty stable through the simulations and the differences are in times when machines are working or idle. Difference in equipment utilisation between different strategies varies only ± 1-3 % units in shorter simulation times and ± 3-6% units when the simulation time is longer. The longer the simulation time and warm-up period get the bigger differences there are in the equipment utilisation compared to shorter simulation times and warm-up periods. *Table 8* shows the example of equipment utilisation when the scheduling strategy used is number 4, "Balancing grades", and the simulation time is 4 weeks after 8 weeks warm-up period and *Table 9* shows the values when the simulation time is 12 weeks and the warm-up period is 5 weeks.

Table 9. Equipment utilisation: Strategy 4 (Balancing grades), simulation time 12 weeks, warm-up period 5 weeks

Resource	Sum	Off	Idle	Transport	Working
Drillrig_1	100%	25%	30%	6%	39%
Drillrig_2	100%	25%	30%	6%	39%
Drillrig_3	100%	25%	31%	6%	38%
Charger_1	100%	25%	22%	8%	45%
Loader_1	100%	23%	32%	3%	42%
Loader_2	100%	23%	31%	3%	42%
Truck_1	100%	22%	32%	30%	16%
Truck_2	100%	22%	32%	30%	16%
Truck_3	100%	21%	32%	30%	16%
Scaler_1	100%	25%	57%	2%	15%
Scaler_2	100%	25%	56%	3%	16%
Boltingrig_1	100%	25%	41%	2%	31%
Boltingrig_2	100%	25%	41%	2%	31%
Shotcretejumbo_1	100%	25%	9%	3%	63%

From the *Table 8* it can be easily seen that the shotcrete jumbo is a bottleneck machine in shorter simulation times. It has a really high working rate, 71%, and is idle hardly ever, only 1% of the time. But when the simulation time and warm-up period increase the working rate decreases down to 63% and idle time increases up to 9%. 63% is still quite high working rate compared to other equipment but probably at this rate the shotcrete jumbo is no more slowing down the work.

With most of the machines the working and idle times stay quite stable when the simulation time increases. With longer simulation times there is a slight decrease in the working time of drillrigs and decrease in idle time. Same thing happens to some other machines as well, like charger and loaders, but these changes are still relatively quite small.

5.2.3 Face Utilisation

In this thesis work a face can have 3 different status; working, waiting and other. Face has a 'working' status when there is actually being done on a face; drilling, charging, loading etc. Face status is 'waiting' when the face is ready for a specific operation but a piece of equipment that is needed to perform that work is not available and the face has to wait until the machine is available. 'Other' status means that there is not actually any work taking place on a face because nothing can be done there. These 'other' operations are ventilation and bolt and shotcrete settling times.

Table 10 shows the face utilisation for each strategy with different simulation times. There are not really significant differences between strategies when the simulation time is the same. The trend seems to be that when the simulation time gets longer the working time increases and waiting time decreases. Of course these figures are not reality; this mine simulation model is a perfect one without any down time or machine failures. No rework is included in the model and of course there is no human factor in the model either. Equipment in this simulation model start working right away when the shift starts or break end, there is always an operator for a machine etc.

Table 10. Face Utilisation.

Warm-up_Sim.time	Strategy	Beh.sched.	1.blast	Max V&%	Bal. %	Diff.face
5_1	Working	30.2%	30.3%	33.3%	32.3%	30.7%
	Waiting	55.9%	55.9%	52.1%	53.5%	55.7%
	Others	13.8%	13.9%	14.6%	14.2%	13.6%
8_4	Working	34.1%	34.5%	36.0%	37.5%	34.7%
	Waiting	52.8%	52.2%	49.9%	48.2%	51.9%
	Others	13.2%	13.3%	14.1%	14.3%	13.4%
5_8	Working	35.5%	36.1%	36.8%	38.9%	35.4%
	Waiting	51.2%	50.5%	49.1%	46.7%	51.0%
	Others	13.3%	13.4%	14.1%	14.4%	13.7%
5_12	Working	39.1%	39.7%	41.5%	41.0%	39.2%
	Waiting	47.3%	46.5%	44.2%	44.0%	46.8%
	Others	13.5%	13.7%	14.3%	15.0%	14.0%

Figure 12 shows face utilisation graphically with the strategy 'Max volumes, max grades' when the warm-up period is 5 weeks and the simulation time is 1 week. *Figure 13* shows the

face utilisation of the same strategy when the simulation time is much longer, 12 weeks. When these two figures are compared it can be easily seen what was mentioned earlier; as simulation time increases, working time increases as well and waiting time decreases. When the simulation time is 1 week face is in 'working' status 33% of the time and in 'waiting' status 52% of the time. Other activities (ventilation, bolt & shotcrete settling times) take 15% of the time.

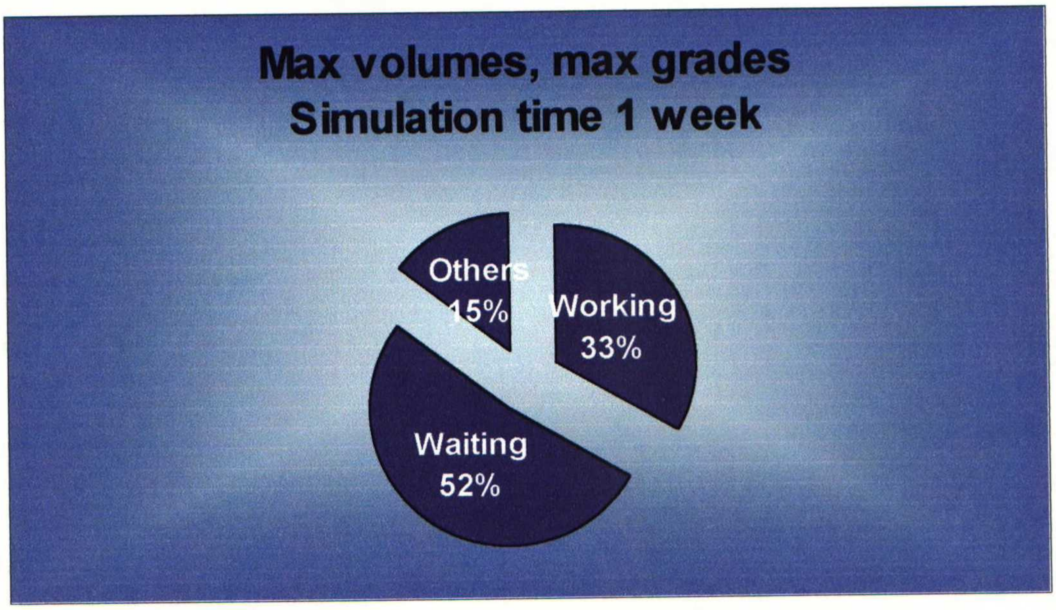


Figure 12. Face utilisation with short simulation time (1 week).

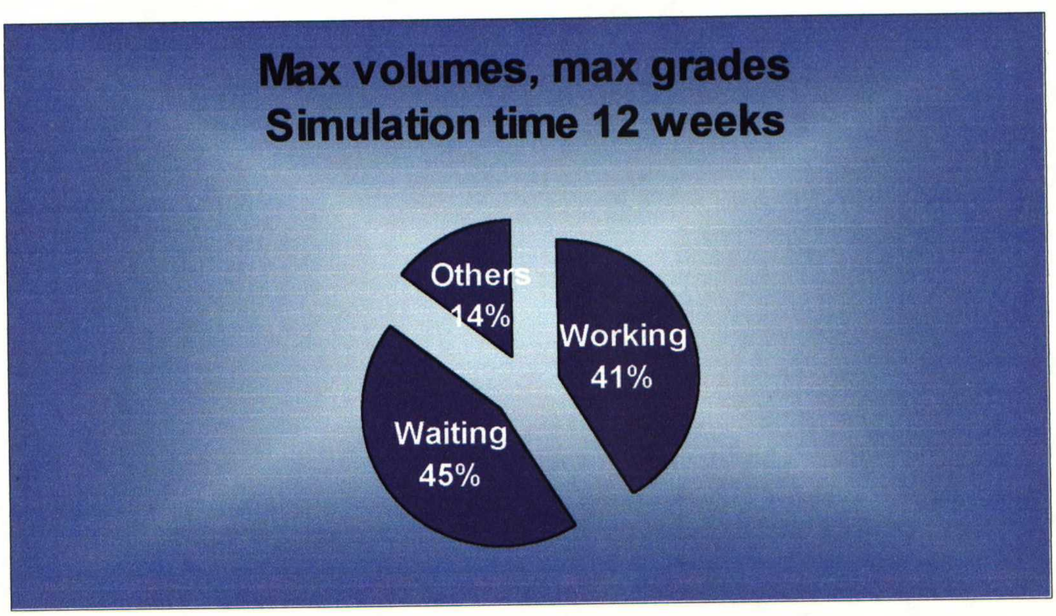


Figure 13. Face utilisation with long simulation time (12 weeks).

When the simulation time is increased to 12 weeks working time has increased quite significantly up to 41% and waiting time has decreased down to 45%. Other activities are taking about 14% of the time.

Table 11 shows the utilisation of faces more detailed when the face is on 'waiting' status.

Table 11. *Face utilisation in waiting status*

Face utilisation	
Drilling	2.3%
Charging	5.3%
Blasting	10.1%
Loading	4.1%
Truck	2.7%
Scaling	0.4%
Cleaning	2.1%
Bolt-drilling	2.0%
Bolting	0.4%
Shotcreting	66.3%
Backfilling	4.3%

Data into the *Table 11* was calculated by summing all the operations waiting hours and then calculating their relative shares from the total waiting time. This table tells how often a face was waiting for a specific operation to begin. From the equipment utilisation one may remember that a shotcrete jumbo was found to be a bottleneck machine, it was working up 70% of its total hours and was idle hardly ever. *Table 11* supports this; a face has to wait for shotcrete to begin over 66% of the total waiting time. That is a lot time compared to other figures that range between 0.4% and 10.1%.

When looking at the *Table 10, Face utilisation*, it seems as 'Balancing grades' gives the best working-waiting ratio. 'Max volumes, max grades' has also a good ratio, the difference between these two strategies is not distinctive.

5.3 Verification and Validation of the Model

Verification is a procedure of making sure that the computer program is performing properly. Verification of this model was done by three people. Each person has experience from the mining industry as well as from AutoMod. Changes in the code were made always when errors were found and as a result there is now a working model. Verification was mostly done by running the model and checking for errors in the code.

Validation is an important part of building the simulation model. This model could not be validated because the model does not totally correspond to real the real Garpenberg Norra mine.

6 CONCLUSIONS

It is possible to test different scheduling strategies and decision rules by using simulation. This requires that the model is accurate enough and there are not too many short cuts taken when modeling the process. A model does not have to be complicated in order to get reliable output data, but a too simple model may lead to results that are far away from the reality.

In this work not one strategy seems to be better than another according to simulation runs made for this thesis work. It only depends on the goals that have been set which strategy to use.

If the target is to get high tonnages mined then either of the strategies 'Most behind the schedule' and 'Max volumes, max grades' should be used as both of them give high ore tonnages compared to three other strategies.

If the target is in metals production strategies to be used are the same ones as previously; 'Most behind the schedule' should be used if high silver production is desired and 'Max volumes, max grades' should be used for high zinc production.

When looking at the equipment utilisation there is no difference between alternative strategies. All the strategies give the similar results.

'Balancing grades' and Max volumes, max grades' are the strategies that give the best working-waiting ratio when face utilisation is under study. There is no significant difference between these two strategies. The best working-waiting ratio is achieved with the strategy 'Balancing grades' when the simulation time is 4 or 8 weeks, 'Max volumes, max grades' gives the best ratio when the simulation time is short, 1 week, or long, 12 weeks.

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APPENDICES

Appendix A CD ROM – mine model, simulation runs